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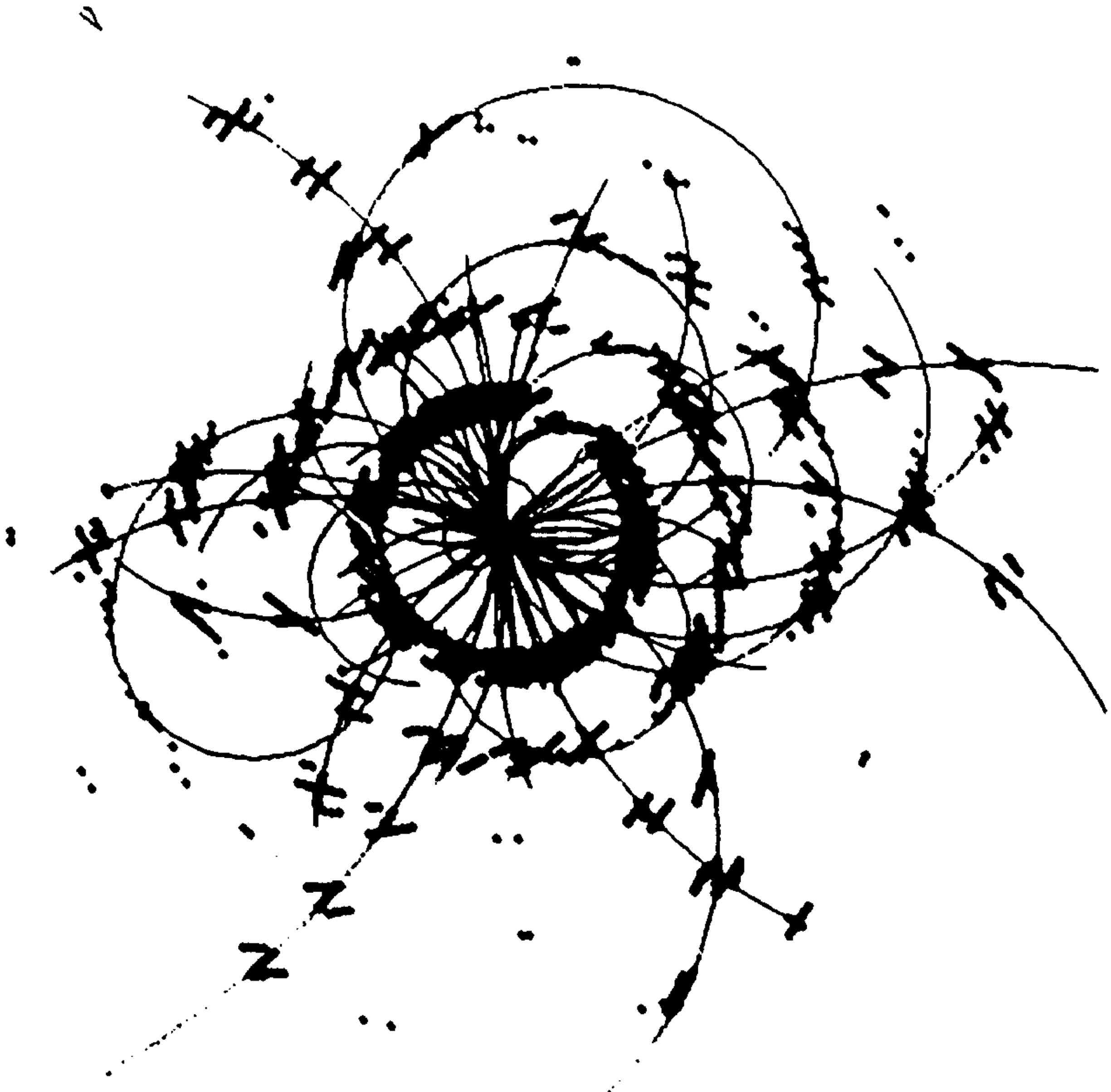
An Operational Approach To High Energy Physics Detectors At Fermilab



Volume 1

AN
OPERATIONAL APPROACH TO
HIGH ENERGY PHYSICS DETECTORS
AT
FERMILAB

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INTRODUCTION

A recent survey (April, 1985) showed that of the 2194 employees at Fermilab only 11% were Ph.D. physicists. Fifty eight per cent had a high school diploma or less. Twenty four percent had A.A. and B.A./B.S. degrees many of which were not in physics. Consequently, the majority of Fermilab's personnel have jobs that somehow interface with high energy physics, yet many of these individuals understand very little about the subject, or how their jobs fit into the larger scheme of things at the Laboratory. When asked by friends, work associates, or family, "What do you do out there?" many of them are not sure. When carrying out their tasks at work, they may run across terms and concepts that they use daily without understanding what they mean. Maybe they've tried to wade into some of the literature in hopes of filling in some of the missing pieces only to be overwhelmed by additional terms and concepts more difficult to understand than the first. This book is written for these people. It describes some of the basic concepts used in high energy physics experiments at Fermilab. Like any technical discipline, high energy physics gave birth to many "buzz words" describing current ideas in the field. Unless one understands this repertoire of descriptions, the real stuff that goes on at Fermilab remains hermetically sealed from the uninitiated.

I wrote this book in reverse order, selecting two experiments as examples (the contents of chapter two), then choosing the contents of the first chapter to fit these examples. The two examples used are experiments E-691 and E-705. E-691 recently finished a data run in the Proton East beamline and E-705 ran in the Proton West beamline. Although these experiments have finished running, they can be used as examples of typical experiments at Fermilab. Most experimental detectors are similar at the component level. They may position their chambers and magnets differently, develop unique computing to accumulate and record data, but at the bottom-line they use many of the same components. I have tried to emphasize these similarities when explaining the anatomy of the two detectors.

I. Physics Background

Over the last fifty years, high energy physicists have attempted to classify the physical phenomena they observed in the laboratory into categories that were useful. A category is a container into which information is placed allowing meaningful interpretations and conclusions about that information. Categories are useful when correlating large numbers of seemingly unrelated facts. For example, if we tried to categorize the buildings in Chicago we could group them by function or structure. In order to sort buildings by function, we must determine how they are used; residence, offices, stores, educational centers, etc. After assigning each building to a category, we would be able to make some interpretations based on the distribution of buildings in each category and come to some conclusions. For example, given the projected birth rate over the next twenty years, the city of Chicago will need more schools. The function category, however, tells us nothing about what the buildings are made of. The second category, structure, would include buildings made of steel, brick, wood, cinder blocks, etc. Once each building was placed in the structure category, we could describe another aspect of the same buildings. Categories originate from questions. What you want to know determines the categories you create and how the facts are sorted.

Classifying particles is similar. We begin with two questions; how do particles behave and what are they made of? From the two questions we create two categories : particle behavior and particle structure. Particle behavior means how they interact with each other and what forces cause those interactions. Particle structure describes their composition. Most particles fall into both of these two categories and the majority of high energy physics experiments done at Fermilab are designed to measure a sub-set of these properties.

A. <u>How Particles Behave; Force And Interaction</u>

Things don´t just happen; every effect has a cause (whether it can be explained or not). We live in a world of motion; some of it we can see with our eyes (cars, birds, the moon), some of it we can´t (elementary particles). All action, whether it be planetary rotation or particle decay, is caused by forces. As a force exerts itself, it causes a change in the thing it acts upon. It speeds it up, slows it down, breaks something apart, or pulls things together.

<u>Forces</u>

In the world of elementary particles, forces cause many types of interactions. They bind particles together, push particles apart, and cause particles to spontaneously disintergrate (decay). What is force? When we observe the electromagnetic force of a magnet attracting a piece of metal, the metal appears to move through empty space (action at a distance). However, current theories state that forces are transmitted by intermediate particles. There are four forces, each having one or more intermediaries associated with it:

1. The gravitational force is mediated by gravitons.
2. The weak force is mediated by W and Z gauge bosons.
3. The electromagnetic force is mediated by photons.
4. The strong force is mediated by color gluons.

The four forces differ in strength and the range over which they operate. The above list is arranged in ascending order of strength. If the strong force is assigned a strength factor of 1 the gravitational force factor would be 10^{-39} (see table below).

FORCE	STRENGTH	RANGE
GRAVITY	10^{-39}	INFINITE
WEAK	10^{-12}	10^{-15} cm
ELECTRO-MAGNETIC	10^{-2}	INFINITE
STRONG	1	10^{-13} cm

The gravitational force effects all matter, but its effect on elementary particles is so slight that it is normally ignored in high energy physics experiments. The effects of gravity become noticeable only when objects have a large mass. The larger the mass, the greater the gravitational force. The total mass of the earth is very large. Consequently, gravity pulls objects to the earth's surface (people, houses etc.). As the mass of an object decreases, the earth exerts less and less force upon it. Compared to the earth, elementary particles are so small that the gravitational effects are not measurable. The range of a force tells how far an object must be from the center of the force before it is effected. The range of the gravitational force is infinite. Even a star many light years from earth exerts a very small force on the earth and all that is on it.

The electromagnetic force effects all charged particles. Like electric charges repel each other and unlike charges attract one another. Earlier in this century, physicists thought that light was a wave much like sound waves. Experiments were performed where a beam of light was directed at a thin metal foil. When the light struck the foil, electrons were emitted from the other side of the foil. As the frequency of the light was increased, the energy of the ejected electrons increased linearly. This phenomenon became known as the photoelectric effect. A common example of the photoelectric effect is the device used to open and close many elevator doors. A beam of light is emitted from one side of the elevator and directed toward a metal plate on the other side. As the light strikes the plate, an electric current is produced and closes the doors. If the beam of light is obstructed by a person entering the elevator, the current ceases and the doors open.

The photoelectric effect suggests that light has the properties of both waves and particles i.e., discreet wave packets which can be located (quantized) at a point in space. These light quanta, commonly called photons, are the particles which mediate the electromagnetic force. The exchange of photons between charged particles causes the attraction or repulsion of charged particles. The electromagnetic interaction is a well understood phenomena and is observable even in the everyday world of large objects (magnets, relays etc.). Like the force of gravity, the electromagnetic force has an infinite range of operation, but unlike gravity it is very powerful. Even the entire gravitational pull of the earth on a paper clip is overcome by a magnet that can be held in your hand.

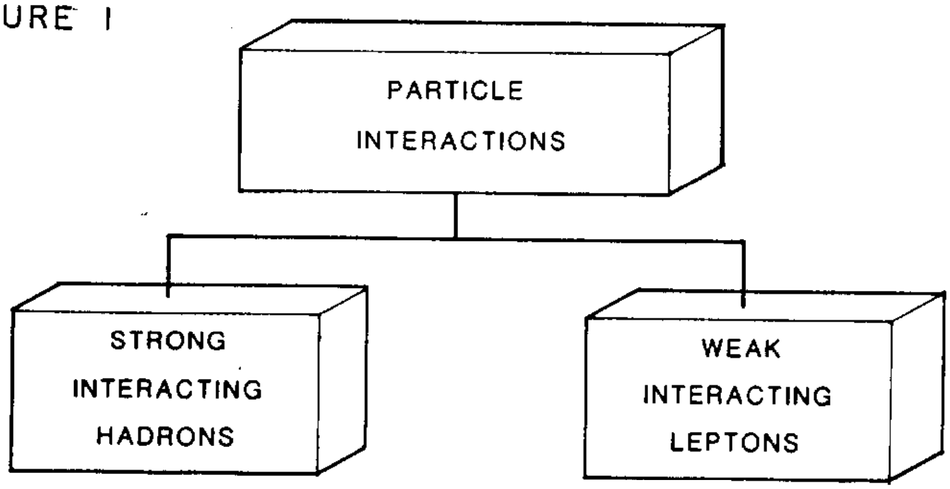
The third force is called the strong force. Let's look at the development of the strong force theory historically. Earlier in this century, Rutherford performed a series of experiments suggesting that hydrogen atoms had a centralized mass composed of a positively charged particle which he called a proton. His data showed that the magnitude of the charge was equal to the charge of the electron, but the sign was opposite. This theory of the nucleus and proton raised an important question when it was applied to atoms having more than one proton in the nucleus. The electromagnetic force is not only very powerful, but its strength increases as the distance between two charges gets smaller. Given both the strength of the force and the tiny distance between protons (10^{-13} cm), how does the nucleus stay together? To answer this question, physicists theorized that there was another force much stronger than the electromagnetic force. They called it the strong force. The fact that the strong force easily overcomes the electromagnetic force at such small distances makes it the most powerful force known to man. The effects of the strong force are dominant whenever it is present. But unlike the electromagnetic and gravitational forces whose ranges are infinite, the range of the strong force is only 10^{-13} cm. Once a particle moves beyond this distance, it is no longer subject to strong force effects. If that same particle moves back into the range of the force, all other forces and effects would be once again subjugated to its power.

The last of the four forces of nature is the weak force. When physicists first observed the radioactive decay of certain elements, they called this process beta decay and named one of the emitted particles beta particles. Since that time, experiments have shown that these particles are in fact electrons. What caused these elements to spontaneously decay? We now know that this phenomenon is caused by the weak force. The weak force is not only responsible for the beta decay of naturally radioactive elements, but it also causes many elementary particles like the neutron to decay. A single neutron isolated from the nucleus lives about fifteen minutes at which time it decays into a proton an electron and an anti-neutrino. Other than gravity, the weak force is the least powerful of the four forces (see Table 1). This brief description of the four forces leads quite naturally to the first two categories of elementary particles: hadrons and leptons.

Hadrons and Leptons

Earlier in this chapter, we used the illustration of classifying the buildings in Chicago by function and structure. We then applied this concept to elementary particles and developed two broad categories into which most elementary particles can be placed: how particles behave and what are they made of. Hadrons and leptons are two sub-categories that describe how particles behave or interact with each other (see Figure 1).

FIGURE 1



Starting from the premise that strong interactions are caused by the strong force and weak interactions are caused by the weak force, we place an elementary particle into a category based on the interactions it participates in. This sorting is possible because strong interactions manifest themselves very differently from weak interactions. One of the main differences is the length of time it takes for the interactions to occur.

Particles that participate in strong interactions are called hadrons (from the Greek root hadrys meaning strong). Two of the most familiar hadrons are the proton and neutron. This is no surprise given the fact that the strong force is responsible for the nucleus staying together. Along with gluing the nucleus together, the strong interaction also causes certain hadrons to decay. A distinctive feature of strong hadronic decays is that they proceed very quickly, some as fast as 10^{-23} seconds. Hadrons which decay this quickly are called resonances and are very unstable.

Particles which participate in non-strong interactions are called leptons (from the greek root meaning weak). As with strong interactions, the length of time needed for a weak leptonic interaction to proceed is a distinguishing characteristic. In most weak decays, the typical time needed for the interaction to proceed is about 10^{-10} seconds. An exception to this rule is the beta decay of the neutron discussed earlier. Although 10^{-10} seconds seems like an extremely short time in the macrocosmic world of eight hour work days (10^{-9} is a billionth of a second), it is rather slow when compared to strong decays which occur in 10^{-23} seconds.

Once we have classified a particle as either a hadron or a lepton, we can make some meaningful statements about how a large variety of seemingly unrelated particles interact with each other. We can also correlate the categories of hadrons and leptons to other interrelated interactions. For example, a proton is classified as a hadron and a muon is classified as a lepton, yet because they are charged particles they are both effected by electromagnetic interaction. A neutron is a hadron and an electron is a lepton, yet neutrons are uneffected by the electromagnetic force. These descriptions allow us to make meaningful interpretations and predictions about how these particles behave; electrons should not interact strongly with the nucleus but they should be attracted to the positively charged protons by electromagnetic attraction.

The current categories, hadrons and leptons, are based upon the observation of these interactions in the laboratory using existing accelerators. Some theorists predict that when accelerators which produce higher energy interactions are built, the strong and weak interactions may become unified. If this occurs, a new category will be needed and the descriptions hadrons and leptons will only be useful descriptors below this energy threshold.

B. What Are Particles Made Of; Internal Structure

The second major category is used to sort elementary particles according to their internal structure. Given our premise that categories are developed in response to questions we ask about nature (or answers nature gives unexpectedly without being asked), we ask the question "Are elementary particles composed of still smaller parts?" Before we proceed, a few things must be explained and defined. First of all, the name "elementary" particle is a bit of a misnomer. The adjective elementary implies that such a particle is not composed of anything smaller. When something is elementary it is the simplest element of something, the least common denominator which cannot be reduced. By strict definition, many of the particles commonly called "elementary" are not in fact elementry.

Most of us learned that the smallest or most elementary parts of an atom were protons, neutrons, and electrons. Today, this is only a half truth; electrons are still thought to be elementary. In the previous section, the category lepton described a group of particles that participated in non-strong or weak interactions. This category does double duty, for all weak interacting leptons are also elementary or fundamental. Should leptons turn out to have internal structure, new categories will be created to describe them. At this point, the category lepton describes both the interactions and the structure of these particles.

This is not true of protons, neutrons, and all other hadrons. Hadrons are composed of more basic particles called quarks. Quarks combine together giving hadrons an internal structure which can be defined and observed in the laboratory.

Once the existence of quarks was established, physicists questioned whether or not a quark could be freed from its parent particle. Current theories state that this is not possible. Quarks seem to be permanently bound within their parent particles. By observing the way the parent particles interact with each other, we can make inferences about the way quarks are situated inside. For perspective, let´s examine the successive levels in the structure of matter (see Figure 2).

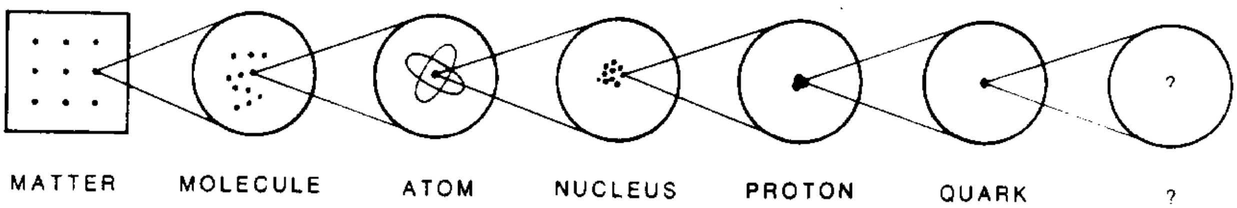


FIGURE 2

If we separate matter into its constituent parts, we find that all matter is made of molecules, and molecules are composed of atoms.

Probing deeper shows that atoms are composed mainly of protons and neutrons. Although atoms also contain electrons, the majority of the atom's mass resides in the nucleus. Penetrating yet another layer shows that protons and neutrons are composed of quarks.

Unlike leptons which have no internal structure, new categories were needed to describe the structure of hadrons. The categories address two questions; how many quarks does a hadron contain, and what kind are they?

Baryons and Mesons

The internal structure of hadrons is classified into two sub-categories; baryons and mesons. A baryon contains three quarks, and a meson contains two quarks (see Figure 3).

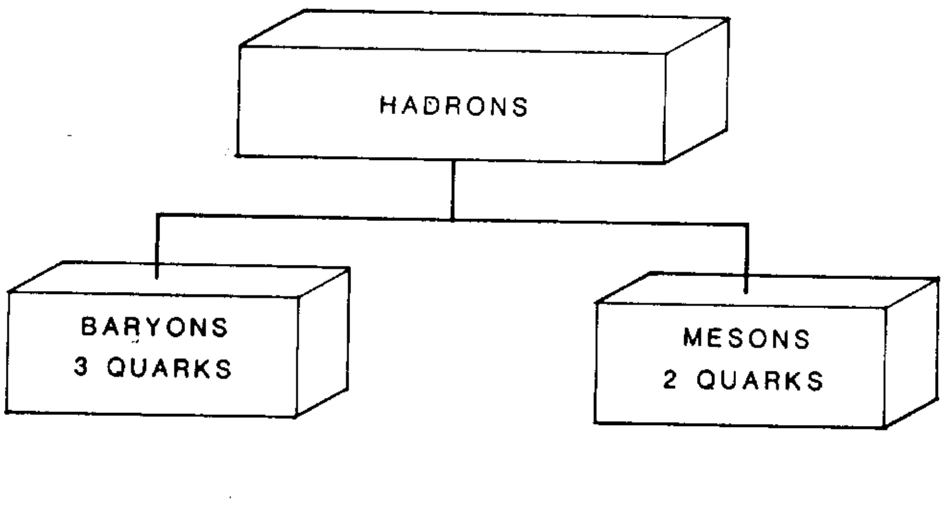


FIGURE 3

When first proposed, the quark model consisted of only three quarks; up, down, and strange (u, d, and s). At that time, all known particles could be constructed from these three quarks. Some theoretical physicists predicted that a fourth quark existed. Since that time, many more quarks have been added to the model. There were three things that made the addition of more quarks necessary. The first thing was related to a very complex mathematical inconsistency if only three quarks existed. The second was the unexpected discovery of new and more massive particles. In spite of the categories and models developed by scientists, nature sometimes volunteers information without reference to the questions we ask. Scientific integrity forces us to allow nature to "call the shots" guiding the forms and structures into which we categorize things. If nature reveals a pattern, we can sometimes extend our models beyond current experimental evidence. When these new particles were first observed, the original three quark model could not explain what scientists were observing.

The third reason for the addition of new quarks was the power of the model to predict other yet unobserved quarks. The usefulness and elegance of any scientific theory lies in its simplicity and power to accurately predict new phenomenon. The elegance of Einstein's equation $E=mc^2$ lies in its simple yet far reaching explanations of energy and matter. Likewise, the quark model was comparatively simple and had the ability to predict the existence of previously unobserved particles. At the present time, matter is believed to be composed of six quarks, and six leptons. The organization of these particles is refered to as the "Standard Picture" (see Figure 4).

FIGURE 4

Constituents in the Standard Picture

Quarks		Leptons	
u	Up	e	Electron
d	Down	ν_e	Electron neutrino
c	Charm	μ	Muon
s	Strange	ν_μ	Muon neutrino
t ?	Top	τ	Tau lepton
b	Bottom	ν_τ ?	Tau neutrino

Quarks and leptons are grouped into pairs called generations. In the first generation, the d quark is partner to the u. In the second generation, the s quark is partner to the c and so on. Each of the three quark generations are associated with a generation of leptons. An important principle in current high energy physics theory is the principle of symmetry i.e. that particles exist in pairs of opposites. Consequently, each quark has an anti-quark as an opposite partner.

Quarks	Leptons
u=up	e=electron
d =down	ν_e =e neutrino
c=charmed	μ =muon
s=strange	ν_μ =mu neutrino
t=top	τ =tau
b=bottom	ν_τ =tau neutrino

All known baryons and mesons are composed of various combinations of quarks and anti-quarks (see Figure 5).

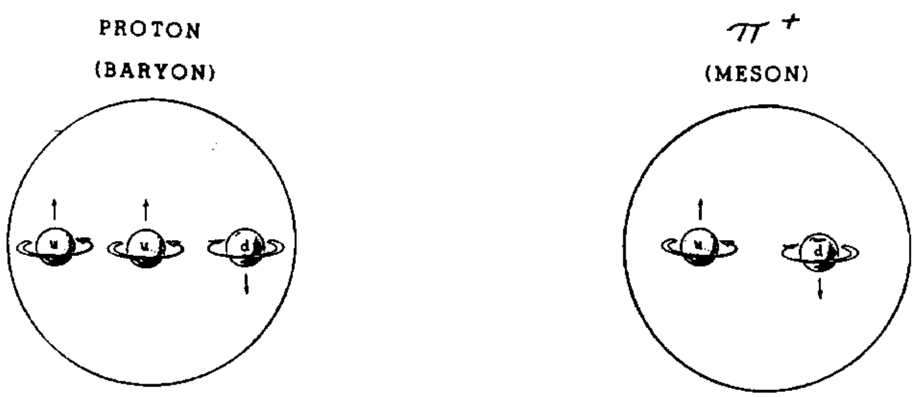


FIGURE 5

The proton (three quark baryon), is composed of two u quarks and one d quark. Much like the earth spinning on its axis, each of these quarks spins on an axis. The arrows in Figure 5 show the direction of spin for each quark. The positively charged pion (meson) is composed of a u quark and a d anti-quark. Mesons always consist of a quark and and anti-quark. Once again, the arrows denote the direction of the spins.

One of the tenants of physics is that fundamental laws of nature are the same at all times. Earlier in this section, we discussed how Rutherford's description of the hydrogen nucleus (being composed of a positively charged proton) seemed to conflict with the electromagnetic law which states that like charges repel each other. This problem was solved by the postulation, and experimental observation, of the strong force. As elegant as the quark model was, it seemed to violate another established law of physics. Previously, Wolfgang Pauli showed that electrons circling the nucleus could not be in exactly the same state simultaneously. This became known as the Pauli Exclusion Principle. If particles such as the proton contain three quarks, two of which are in identical states, this violated the Exclusion Principle. Normally, when an established law of physics appears to be violated the violation points to hidden symmetries or other yet unobserved parameters. This problem forced theorists to once again extend the model. Each quark type (up, down, charmed, etc.) was designated as a flavor and each flavor came in three colors (red, green, and blue). By assigning the additional attribute of color to each of the quark flavors, it was possible for a proton to contain two u flavored quarks having different colors and not violate the Exclusion Principle.

Quark Model Dynamics

Of all the baryons, only the proton is stable. The stability of a particle is determined by how long it exists (lives) before decaying into other particles. The longer the lifetime the more stable the particle. Experiments are currently being conducted to measure the lifetime of the proton. Current models postulate a lifetime of about 10^{31} years at which time the proton decays into other particles (and the experimenters are not around to publish their results). The neutron lives about 918 seconds (15 minutes) then decays into a proton, electron, and a neutrino. The lifetime of the proton is consistent with the stable properties of atoms. But how can atoms be stable for millions of years if the lifetime of the neutron is only 15 minutes? The answer is related to the different strengths of the strong and weak forces. The neutron decays by weak interaction having a strength factor of 10^{-12} and a range of 10^{-15} cm (see Table 1). The strong force has a strength factor of 1 and a range of 10^{-13} cm. As previously mentioned, the effects of the strong force are always dominant within its range of operation. If the strong force overpowers the electromagnetic force, preventing the break-up of the nucleus (electromagnetic force is 10^{-2} in strength), it easily overcomes the effects of the weak force preventing neutron decay. However, should a neutron be knocked out of the nucleus, moving beyond the range of the strong force, the weak force will once again become dominant and the neutron will in fact decay. So the stability of matter is a result of the strong force's ability to prevent spontaneous particle decay. If the strong force should suddenly stop exerting its power over stable nuclei, every neutron would be freed and decay in about 15 minutes.

This stability is characteristic only of protons. Other particles which participate in strong interactions are very unstable. These particles, called resonances, decay in about 10^{-23} seconds by the strong interaction. One example of a resonance is the delta (Δ) which exists in four different charge states (++, +, 0, -). Resonances are excited states of matter and energy which are produced when particles interact. They don't exist naturally in our world. A particle resonance like the delta, can be compared to a musical resonance or pitch. By taking a metal string and stretching it to a particular tension on a guitar, we can create a resonance when the string is plucked. When the motionless string is plucked, the guitarist imparts energy to the string causing it to vibrate at a particular pitch or resonance. Once the energy imparted to the string dissipates in the form of sound waves, the resonating ceases. Creating particle resonances is similar. Obviously we cannot pluck a proton with a pick, but we can impart energy to it by hitting it with another particle. By imparting energy to protons, resonances such as the delta are created and die in much the same way the music of a symphony lives and dies. When a delta is produced, it lives for about 10^{-23} seconds then decays into a proton and a neutral pion (π^0). The decay is symbolized like this:

$$\Delta^+ \rightarrow p + \pi^0$$

The decay pattern shown above is useful in showing the overall results of a decay, but it does not describe the steps involved in the decay process. Using the categories of particle behavior and particle structure, we can make inferences about these steps and describe how the decay proceedes. These descriptions should agree with the above decay pattern i.e., we must start off with a delta and end up with a proton and a neutral pion.

First, if the delta is a strong interacting hadron, we should be able to predict some of its behaviors. The delta should interact strongly with the nucleus then decay very quickly. The delta exhibits both of these behaviors. It is produced by imparting energy to a proton in the nucleus and once created it decays in about 10^{-23} seconds. Second, because it is a hadron our category of internal structure claims that it is made of quarks. To be more precise, the delta is an excited state of a proton, a 3 quark baryon (see Figure 6).

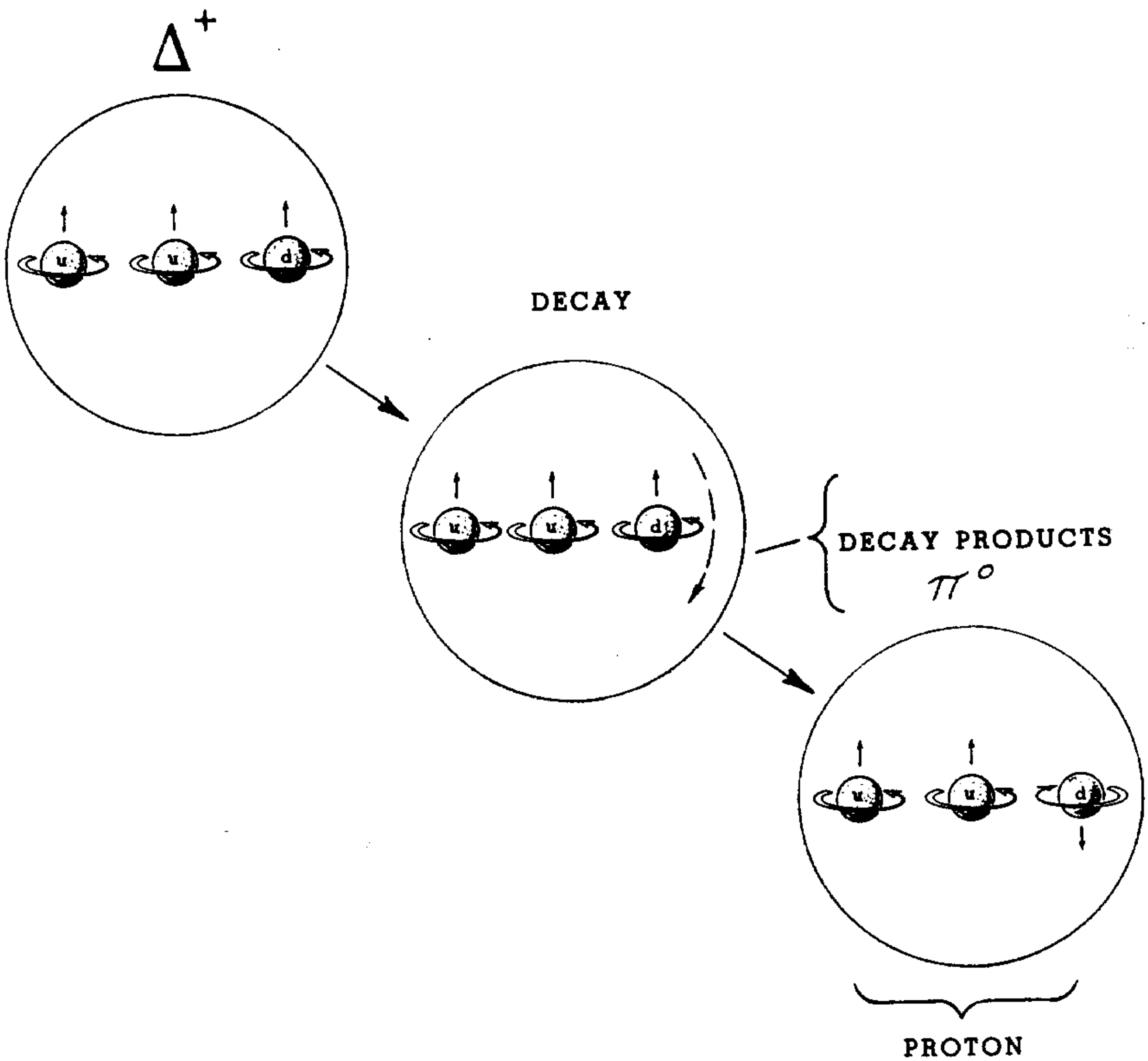


FIGURE 6

The delta is composed of two u quarks and one d quark with all the spins aligned in the same direction. Let's examine the entire process. If we place a fixed target in the path of a proton beam, the protons and neutrons in the target and the protons in the beam all become potential delta candidates. As one of the protons in the beam interacts with a proton in the target, it imparts energy to the target proton. In the case of the delta, this energy manifests itself in the alignment of the three quark spins (see Figure 6). But the delta cannot remain in this state longer than 10^{-23} seconds before decaying. When the decay occurs, the spin direction of the d quark reverts back to its original direction and the remainder of the energy imparted in the initial interaction is converted into a neutral pion and emitted during the decay. Hence we describe the decay as:

$$\Delta^{+} \longrightarrow p + \pi^{0}$$

The proton and the the pion resulting from the decay are called decay products. The decay of the delta is a relatively simple change in the quark structure. Notice that none of the quarks change flavor; the u's and d maintain thier identity. The only change is the spin direction of the d. This explains why the decay proceeds so rapidly. In the world of quarks, changing spin direction occurs very easily, but this is not the case with all particle decays. Some decays involve more complicated manipulations and transformations of their quark structure.

C. Unusual Particles

What do we mean by "unusual" particles. Protons, neutrons, and electrons are common, they are every where. They don't have to be specially manufactured like the delta. By this definition, the delta is an unusual or rare particle, but it is still composed of u and d quarks which quickly revert to two particles which are also composed of u and d quarks. Currently there are hundreds of unusual particles and resonances composed of quark combinations which include the other 4 quarks. Some of these particles were predicted by theories, others were discovered pretty much by accident when nature gave experimenters answers that they had not asked for.

Strange Particles

In the early 1950's before the quark model was proposed, a new and unexpected particle was discovered whose mass was greater than the proton. This particle was called the sigma (Σ^+). The decay is symbolized like this:

$$\Sigma^+ \longrightarrow p + \pi^0$$

Notice that the final decay products are identical to the delta particle (see Figure 6). If the decay products of the sigma are identical to those of the delta, why should we suspect that they come from a different parent particle? There are several things that don't add up.

First of all, the mass of the sigma is larger than that of the delta. Secondly, it decays in 10^{-10} seconds, 13 orders of magnitude slower than the delta, yet yields identical decay products. As mentioned earlier, when an apparent violation of a known law of physics occurs the violation normally points to a new series of phenomena. And so it is with the sigma. Because of its weird behavior, physicists call the sigma a "strange" particle.

In retrospect we see that the increased mass of the sigma implies that the strange quark (s) is more massive than the u and d quarks. This explains why the sigma is more massive than the delta; first problem solved. But it does not explain the increased lifetime of the particle. The answer to this discrepancy necessitates a more thorough understanding of the steps involved as the decay proceedes. Given the difference in decay times between the delta and the sigma, the decay should involve additional or intrinsically more difficult steps.

The sigma is a baryon containing two u quarks and an s quark. When the decay occurs, the s quark changes flavor and becomes a d quark, but the transformation does not effect the direction of the quark's spin. Because the s quark is more massive than the d, conservation laws demand that this mass be accounted for in the decay products. The extra mass is emitted as a neutral pion (see Figure 7).

The steps involved in the sigma decay differ from the delta at two points. Unlike the delta, the spin of the changed quark remains the same, but the quark changes flavors. The simple change of the delta's spin direction allows the decay to proceed very rapidly. But the changing of flavor appears to be a much more complicated and time consuming process. This suggests that decays can occur quickly only if the quarks involved do not change flavors. Presently, experimentalists have observed many other strange particles in the laboratory.

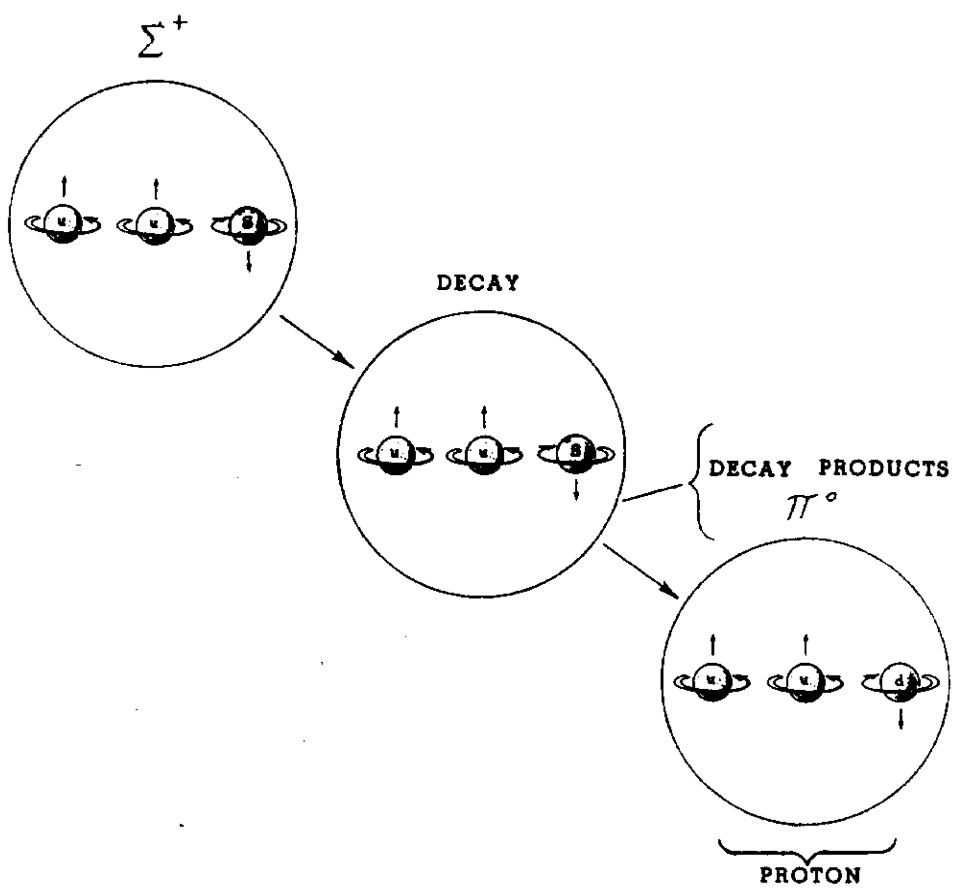


FIGURE 7

Charmed Particles

We have already discussed the power of the quark model to predict the existence of new previously unobserved particles. Much like the first generation of quarks formed a pair (u and d), some theorists predicted that the s quark also had a mate. Normally, when such a prediction is made, physicists propose experiments and build detectors to search for the new particles. Such was the case with the fourth quark. The existence of the charmed quark was established by two independent experiments conducted in mid-1974. One experiment was performed at Brookhaven National Laboratory under the leadership of Samuel C.C. Ting of MIT. The other was headed by Burton Richter at SLAC. Using two different experimental techniques, they independently discovered the same particle at about the same time. The MIT group called the new particle the J particle, and the SLAC group named the same particle the psi (ψ) particle. After the data analysis of both experiments was complete and both groups were ready to publish their results, they learned that they had in fact discovered the same particle. Today the particle is called the psi/J meson. The increased mass of the psi/J confirmed the existence of a fourth more massive quark, the charmed quark (c). The differences between the psi/J and the sigma and delta are two-fold. The particle is more massive, and it decays in 10^{-20} seconds. This was 10 orders of magnitude shorter lived than the sigma and 1000 times longer lived than the delta (see Figure 8).

PARTICLE	MASS	LIFETIME
PROTON	0.9 GeV	10^{31} YEARS
Σ^-	1.197 GeV	1.5×10^{-10} SEC
ψ/J	3.095 GeV	10^{-20} SEC

FIGURE 8

Figure 8 shows a sample of particles from each category. Notice the variations in lifetime and the increasing mass as we move from the proton to the charmed particles. The quark structure of the psi/J and D^0 charmed mesons are shown in Figure 9. Like all other mesons, they contain a quark, and an anti-quark. But unlike the neutral pion given off in the delta and sigma decays, one or more of these quarks is charmed.

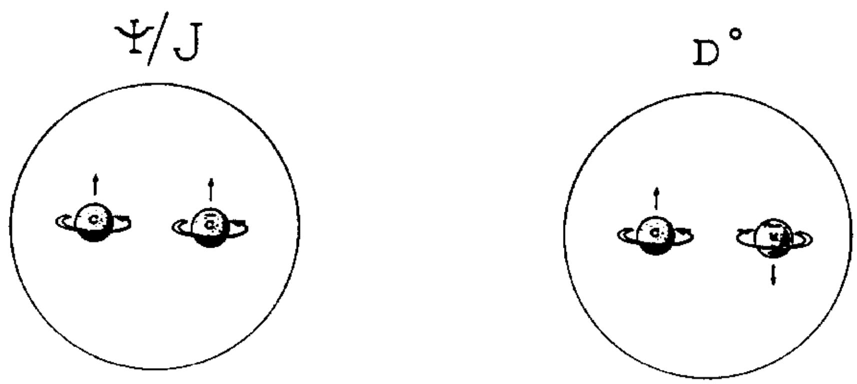


FIGURE 9

Many charmed particles have been discovered since the psi/J. These particles are grouped into families each having different mass members (see Figure 10). Figure 10 shows three varieties of psi particles; the psi with a mass of 3.095 GeV/c, the psi prime with a mass of 3.684 GeV/c, and the psi double prime with a mass of 3.772 GeV/c.

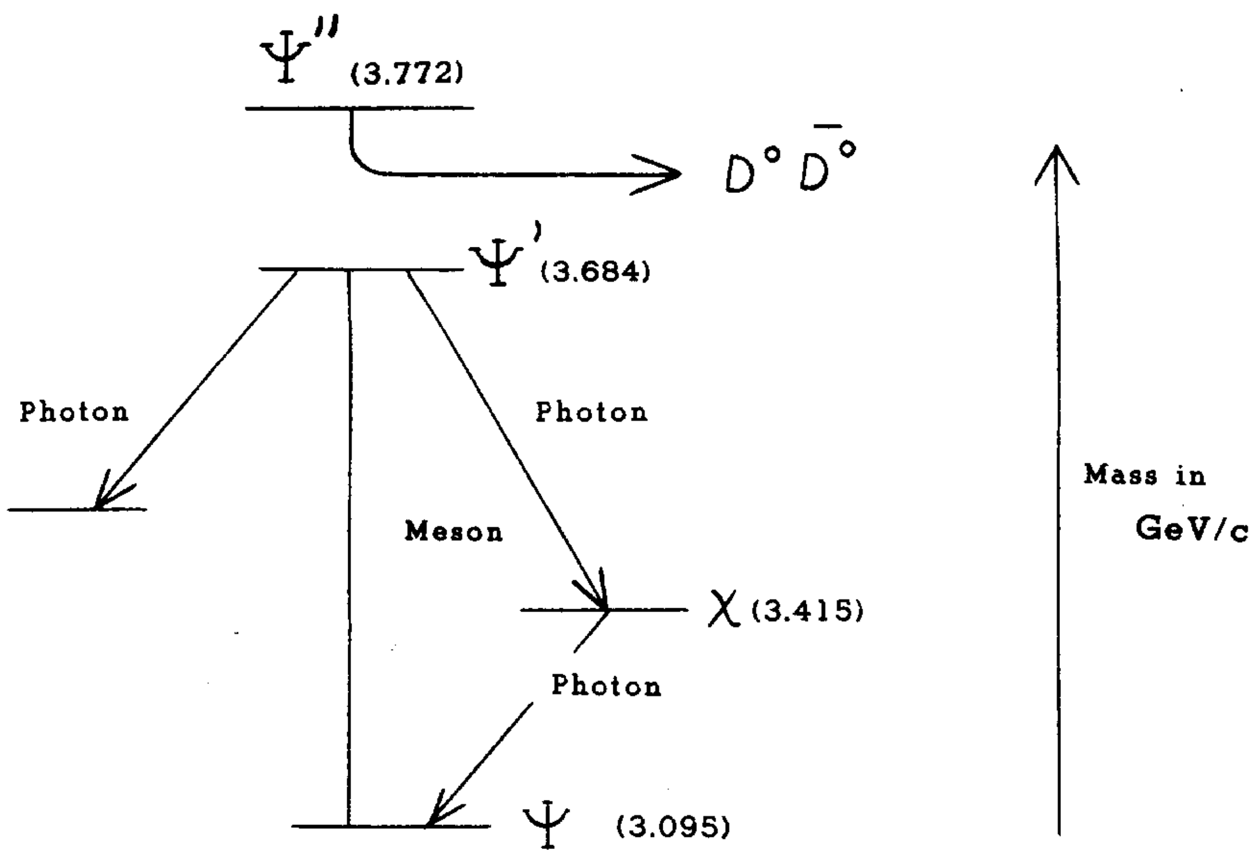


FIGURE 10

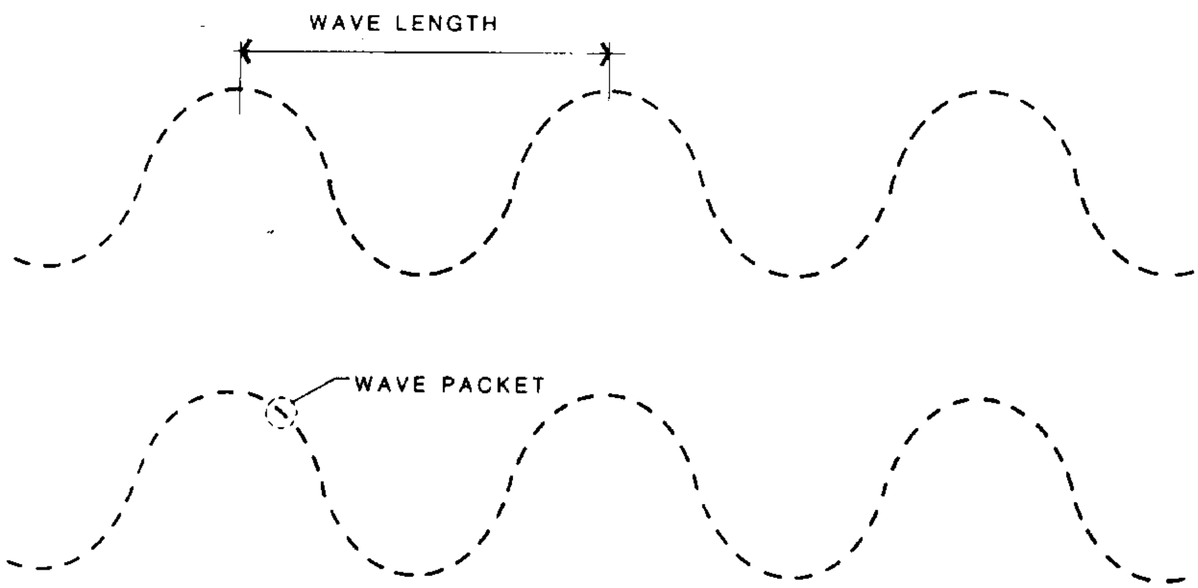
Notice the progressive decay steps through which these charmed particles proceed. For example, the psi prime decays to a lower mass member chi (χ) meson and the difference in mass is emitted as a photon. The energy of the photon must be 0.269 GeV/c in order for the total energy of the interaction to be conserved. The chi subsequently decays into a psi and also emits the mass difference as a photon.

The emission of photons in charmed decays is similar to what happens when a proton passes through a scintillating material. As the proton travels through the plastic, it passes near some of the electrons orbiting the atoms in the plastic. If the proton passes close enough, its positive charge attracts the negatively charged electron imparting enough energy to lift it to a higher orbit. The electron travels in the higher orbit for a time, but it cannot remain there indefinitely. When the electron snaps back to its lower orbit, conservation laws demand that the energy imparted in the interaction be accounted for. The energy is given off as a photon. The photons are then gathered to a photomultiplier and read-out as a voltage. The decay of charmed mesons follows the same principles of photon emission. As will be seen in Chapter II, one of the most important ways to detect charmed particle decays is to look for this emitted photon.

<u>Photoproduction of Charm</u>

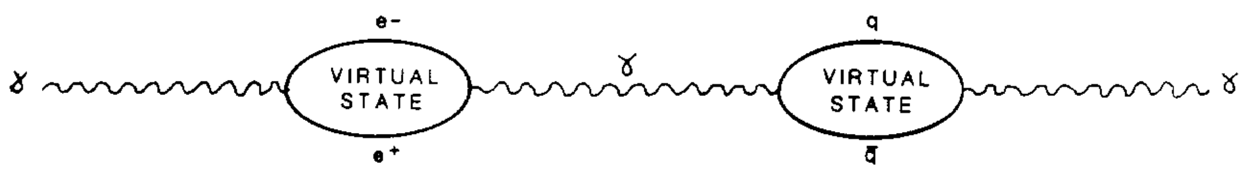
Up to this point, all the rare particles discussed were produced by rearranging the quark structure of baryons and mesons. Another way to produce charmed particles is by a process called photoproduction. An example of an experiment using the photoproduction technique is given in chapter II (E-691). The purpose of this section is to describe the theoretical basis of the process.

Earlier in this chapter, we described a principle called the photoelectric effect. The photoelectric effect shows that photons exhibit the properties of both waves and particles. Actually, whether a photon is a wave or a particle depends on how we choose to observe it. When we observe it as a wave, we can calculate its energy by determining the wave length of the light. If we locate this wave at a point in space, it acts as a wave packet/particle (see Figure).

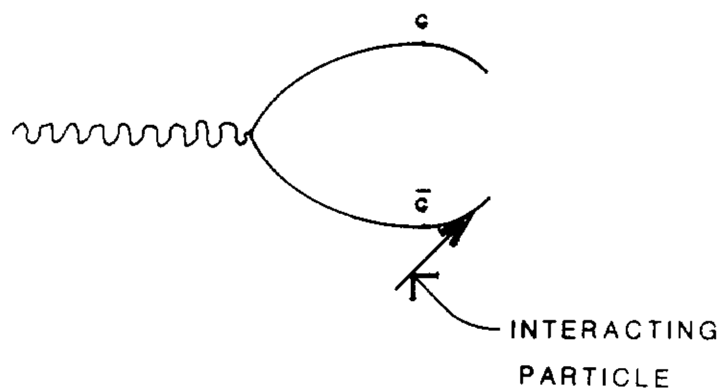


Photons also exhibit another quality which becomes the theoretical basis for the photoproduction process. As a photon moves along at the speed of light, theory predicts that a small fraction of the time it exists in what is called a virtual state. The phenomena of virtual as opposed to real states are not easily explained by conventional models. When a photon is "real", it is in fact a photon. When a photon is in a "virtual" state, its identity is up for grabs. It exhibits all the properties of a photon, but theoretically it can become a hadron or a lepton or remain a photon. Physicists can describe virtual states mathematically and prove the theorems by experiment (E-691). But when the mathematical models are deemed off-limits because of the reader's (and writer's) level of understanding them, it becomes very hard to describe this process in any concrete way. But let's give it a try!

A graduate student who absolutely hates working nights is running a midnight shift on any Fermilab experiment. He's burned out, the spill's been bad, intensity has been either too low or too high, and he's been calling the Operations Center all night trying to keep the beam tuned to half a wire resolution on a half mil SWIC. Got the picture? He's frustrated and angry maybe at no one in particular. The guy that's suppose to relieve him strolls in right on time. The "night shift hater" briefs his partner on the shift happenings and tries not to let on that he's upset. His relief asks him "Is there something wrong"? "No!" he answers. But it's apparent to his friend that there is <u>something wrong!</u> His anger is "virtual". Although he exhibits all the properties of a calm guy, the virtual anger is easily transformed into real anger when his buddy tells him he´s coming in 3 hours late for the next 2 weeks. This outwardly calm guy explodes and lets his friend have all the anger that has built up over the course of the shift. But the anger is´nt virtual anymore; it´s real! Using this far out (virtual) example as a spring board, let´s get back to virtual photon states. When a photon is virtual, it appears to be a photon (much like the graduate student appears to be calm). But if another particle interacts with it imparting energy to it (the last straw, being 3 hours late for two weeks), the photon is forced to become real (the student begins to scream). The Figure below is a schematic drawing of virtual photon.



While the photon is virtual, the probability exists that all the components needed to produce an electron positron pair or any quark anti-quark combination are present in the virtual photon. It's a state of potentiality. Let's assume that a virtual state contains two virtual charmed quarks like the ones pictured in the Figure below.



If another particle interacts with one of the virtual quarks giving it a kick away from its partner, the effective mass of the pair becomes very large. If the mass reaches, for instance, 3.772 GeV/c (the mass of the psi double prime) the virtual quarks become "real" and a psi double prime is produced. This is a slightly different process than the ones previously discussed. The other processes create charmed particles from interactions of quarks that already exist (quark annihilation for instance). These and other production processes are described more fully in Chapter II (E-705 and E-691).

The Bottom And Top Quark

The latest additions to the list of quarks are called bottom and top (b and t). The b and t quarks are sometimes refered to as beauty and truth, but the names bottom and top have become the standard nomenclature. During the mid-1970's, a group of physicists under the direction of Leon Lederman designed an experiment (E-288) and built a detector at Fermilab to search for new and more massive particles. In 1977 the group announced that they had discovered two new particles which they called the upsilon (Υ) and the upsilon prime (Υ'). These two particles were more massive than any previously observed particles and the increased mass implied a composition of more massive quarks. The upsilon has a mass of 9.5 GeV and the upsilon prime has a mass of 10.0 GeV (see Figure 11).

FIGURE 11

FLAVOR	PARTICLE	MASS
u,d	PROTON	0.9 Gev
s	Σ^-	1.197 Gev
c	χ	3.415 Gev
b	Υ	9.5 Gev
b	Υ'	10.0 Gev

Because the upsilon is a meson, it is composed of a quark and an anti-quark. Figure 12 shows the quark structure of both mesons. Both particles are composed of a b quark and an anti-b quark with their spins aligned.

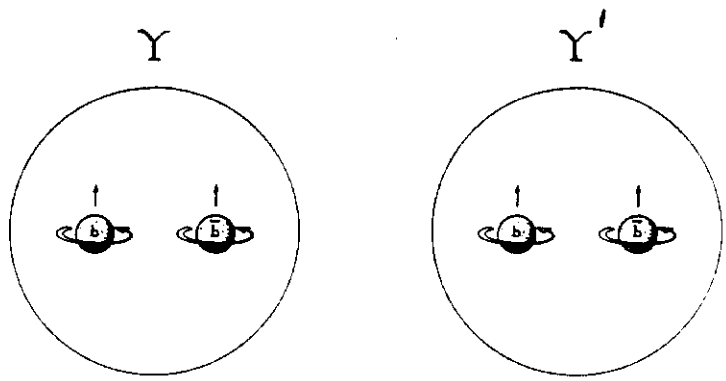


FIGURE 12

The fact that quarks seem to group themselves in pairs suggests that the b quark has a partner. This particle was called the t quark. Physicists began to search for the t quark, predicting that its mass should be greater than the mass of its partner.

In July 1984, a group of scientists at CERN announced preliminary evidence of the t quark. The t quark events were detected in a massive colliding beams detector called UA1. The evidence has become less tenable with more thorough data analysis, but higher energy colliders like the Tevatron may be able to substantiate the existence of t quarks by exploring higher energy regions beyond the capability of the CERN collider.

D. Accelerators

Earlier in this century, all particle experiments used particle projectiles that occured naturally. Rutherford used the alpha particles that were emitted by naturally radioactive materials. Anderson discovered the positron by analyzing collisions caused by cosmic rays. Although these sources of particles were free for the taking i.e., physicists did not use man made machines to create them, the experimenters had no control over the energies of the particles, the time they appeared, or the number of particles delivered by nature. A physicist who placed a chamber on the top of a mountain had to accept whatever particles came, at a variety of energies, and sometimes wait long periods of time to accumulate even a small sample of events. Physicists needed a way to produce particle beams when they wanted them. By building machines that produced these beams, experiments could be carried out using specific particle energies and intensities, obtaining more precise measurements and larger data samples.

In 1929 Ernest O. Lawrence discovered a way to accelerate particles by circulating them in a electromagnetic field. This device was called a cyclotron. In 1932, a cyclotron having a diameter of 11 inches accelerated particles to 1 MeV by circulating the particles through a constant magnetic field. Although these particles could be produced as needed, there were limitations on the energy levels that could be achieved with such machines. This problem was solved by the design of an accelerator called a synchrotron. The synchrotron was designed so that as the energy of the particles increased, the magnetic field which counteracted the centrifugal force also increased. This kept the particles moving in a circle around the ring.

Since that time, accelerator physicists have designed accelerators that produce particle beams of higher and higher energies. Increased ring diameter and design of more powerful magnets have been the engineering goals that made these new machines possible. But why are higher energy accelerators so necessary? The answer to this question may already be apparent in light of the previous sections, but a brief explanation is provided in the next section.

Why Are Higher Energies So Important?

Albert Einstein was the first to suggest that energy and matter were actually different forms of the same thing ($E=mc^2$). Although the total amount of energy in any interaction is always conserved, it can be changed from energy to matter and back to energy again. The rest energy/mass of a proton is about .9 GeV/c. The Tevatron takes these protons and accelerates them to an energy/mass of 800 or 1000 GeV/c. The added energy/mass that a 1000 GeV/c proton possesses is called its relativistic mass. Placed in the macrocosmic world, 1 TeV is a very small amount of energy. If a 1mm diameter rain drop strikes your hand, it delivers about 26 TeV of energy. But when 1 TeV of energy is concentrated in an area the size of a proton whose rest mass is thousands of times smaller, the extra energy can be converted into rare types of leptons and hadrons. The higher the relativistic mass of the incident particle is, the more energy that is available to produce secondary particles. If additional leptons and quarks exist, they will probably be more and more massive. Consequently, future accelerators must produce beams with higher relativistic mass in order to explore these energy regions. The proposed SSC is such a machine. Of all the quarks discussed in this chapter, the b and t quarks are the most massive (upsilon mass=9.5 GeV/c). But why does it take 400 GeV/c incident protons to produce a 9.5 GeV/c particle. This question is addressed in the next section.

Fixed Target/Colliding Beam Physics

When a 1 TeV incident proton beam strikes a fixed target, the majority of the relativistic mass imparted in the acceleration process is used up in the production process. Consequently, only a fraction of the beam energy is available for the creation of new particles. Because the momentum of the incident beam must be conserved, the majority of the extra energy is used to produce secondaries whose motion is in the forward direction. Consequently, it takes a large amount of incident particle energy to produce high energy secondary particles.

The alternative to fixed target physics is colliding beam physics. When two particle beams are collided together, the sum of the two energies is available for the production of new particles. If more massive quarks exist, the energy efficiency of colliding beams may be able to produce them.

II. An Anatomy Of Two Experiments

Having described some of the fundamental principles of high energy physics in Chapter I, this chapter applies these principles to two experiments that have run at Fermilab. Although the experiments have already completed their data samples, understanding how they work is a useful paradigm for understanding many Fermilab experiments. The first section of this chapter is a transitional section which discusses the relationship between empirical observations and theoretical postulations. The last two sections describe the operation of experiments E-705, and E-691. Each section describes how the secondary beam is produced from Tevatron protons, a description of the physics principles being studied, and a simple explanation of why the collaboration did that particular experiment. Finally, the detector is described component by component including what particles cause them to trigger.

A. Theory And Experiment; An Analysis

What are theories and hypothesises, and how do they differ from physical laws? Why perform experiments at all? According to Webster a theory is "an ideal or hypothetical set of facts, an unproved assumption". A hypothesis is "a tentative assumption made in order to draw out and test its logical or empirical consequences". Theories are ideas about the way things are. But sometimes the most wonderful and impressive theories are matters of opinion that can not be proven. People disagree about ideas and many times both sides of the argument are equally persuasive. When Socrates was on trial in Ancient Greece, he responded to the charges against him by stating "How you, O Athenians have been affected by my accusers, I cannot tell; but I know that they almost made me forget who I was-so persuasively did they speak; and yet they have hardly uttered a word of truth".

In the physical sciences a law is "the observed regularity of nature". The key difference between a physical law and a theory or hypothesis is the repetitive observation of a phenomenon. Experiments can settle disagreements between opposing theories by testing them over and over under controlled conditions. Experimental evidence of previously unobserved phenomena can also give rise to new theories. A theory is "useful" only when it predicts and explains the way nature behaves as observed in the laboratory or nature. In order to prove a theory, it must pass the intense scrutiny of experiment, sometimes by different people, each obtaining the same results.

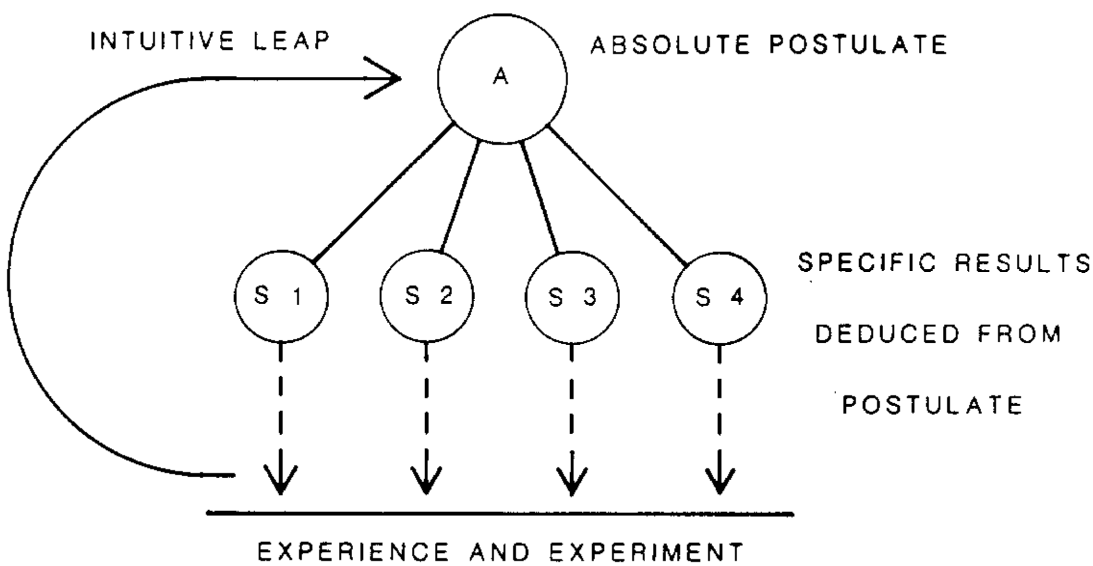
Some theories cannot be tested. Whether a theory can be tested or not is determined by the kinds of ideas that the theory asserts. At this point, let's define a couple of terms; epistemological and ontological. When a theory cannot be tested because of epistemological limitations, the limitation is due to <u>our current knowledge</u> about the subject. If we knew more or had more sophisticated technologies, we could eventually overcome this limitation and design an experiment, or series of experiments, to test the theory. An example of overcoming epistemological limitations is the current use of silicon microstrip vertex detectors. Silicon microstrip vertex detectors are used to measure the decay vertices of charmed particles with high resolution. They contain thousands of wires which can locate the position of a particle to within a distance of one seventh the thickness of a human hair. Previously, these decay vertices were unobservable because the detectors being used could not make accurate enough measurements so the events went undetected even though theory claimed they happened. Another example is the use of increased computing power to decrease the dead time of a detector, the time needed to observe and record events which take place in the detector. The development of new detectors and more powerful computers have pushed back the epistemological boundaries of high energy physics experiments.

But some theories cannot be tested because of ontological limitations. An ontological limitation cannot be overcome regardless of how much we know, it is not knowable. The speed of light in a vacuum is an ontological limitation, the "speed limit" of the universe that cannot be exceeded. One could devise many theories about particles that travel faster than the speed of light, the theories may even hang together mathematically, but there is no way to test them. Consequently, they remain ideas, fantasies, unprovable.

Another example of an ontological limitation is trying to accurately measure certain properties of particles simultaneously. In Chapter I (Photoproduction) we said that particles exhibit the properties of both particles and waves. If we want to measure the momentum of a particle we measure its wave length. If we attempt to observe that wave at a point in space, we no longer see it as a wave, it is a particle. It is ontologically impossible to observe a particle in both states simultaneously, we cannot always have our cake and eat it too! This limitation is described by a theory called the Uncertainty Principle. The Uncertainty Principle tells us what we can and cannot know about particles. In the macrocosmic world of large objects (trees, people, etc.), we "see" or "observe" things differently than in the world of elementary particles. As you look at this page, photons from a light source are striking the paper, bouncing off of it and entering your eye. The image of the page and print is reflected in your eye and your brain records the image. This book is rather large compared to the photons that are striking it. Although they hit the page and scatter to your eye, the collisions are not powerful enough to move the book. The only way to observe elementary particles is to make them do something, hit them with something. Unlike this book, when we hit a single proton with a high energy photon the force of the collision sets the proton in motion. Imagine hitting this book with fast moving tennis balls. It would not take too many collisions to knock the book off the table. By observing where the photon/proton interaction occured, we can determine the position of the proton with fairly high accuracy. But hitting the proton sets it in motion and we are no longer certain of its momentum. When we cause an interaction with elementary particles (hit them with other particles), it is impossible to observe them without effecting them in some way. The uncertainty principle states that it is ontologically impossible to know both the position and momentum of a particle simultaneously with absolute precision. It is not a question of how much we <u>know,</u> or the state of our technology, we can never build a detector that will measure these properties simultaneously.

So there are things we can know and things we can't. One could theorize all day long about designing a detector to precisely measure position and momentum simultaneously, but there is no way to test the theory. This theory is not useful, it's a waste of time to think about it. These ontological limitations set the boundaries of what an experiment can and cannot measure. Because of the time, talent, and money involved in building and running an experiment at Fermilab, or anywhere else for that matter, those who approve the experiments must be sure that the experiment will actually do something useful. But do ontological limitations mean that we have arrived at the ultimate theory, a theory that will forever remain unchanged? History has shown that many theories which we thought described ontological limitations were destroyed by an insightful mind who theorized that the limitation was in fact a lack of understanding on our parts. One such individual was Albert Einstein. In a letter to Maurice Solovine, Einstein describes the model he used to develop his theories. This model beautifully describes the relationship between the creation of new theories and the problem of testing them. Let's look at the model in the context of history.

In 1905, Einstein published three papers that changed physics permanently. One of them implied that light was a particle as well as a wave (the photon). His observations were based on earlier results of Max Planck's photoelectric effect which we discussed in Chapter I. But at that time there was no way to experimentally check Einstein's theory. Millikan, an American physicist, spent years trying to devise a method for testing the equation without success. In 1915, ten years later, Millikan was quoted as saying "Despite... the apparent complete success of the Einstein equation, the physical theory of which it was to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it". But Einstein stood firm in spite of the lack of experimental evidence. It wasn't until 1923 that Compton and Debye confirmed the theory by scattering photons off of electrons. The Figure below is a copy of the diagram Einstein sent to Solovine describing how he originated his theories.



All theories begin with experience and experiment i.e., what we already know about our world. In Einstein's case, this was the data results from the photoelectric effect experiments and all previously proven physical theories. The next step involves an intuitive leap far beyond where any experiment could check the results. Einstein called this leap an absolute postulate which, in this case, stated that light was a quantized wave packet/particle. Next, the absolute postulate is used to deduce specific results that can be experimentally checked. In other words, if the absolute postulate is true we should observe a specific effect, i.e., photons should exhibit the properties of other particles. The last step is to design an experiment that will look for these effects and either prove or disprove the theory. Compton did this by scattering photons off of electrons. If the experiment proves the theory correct, as it did in this case, then the results of that experiment become part of the initial depository of experience and experiment giving rise to other intuitive leaps and new absolute postulates. And science moves on!

Sometimes an unexpected phenomenon is discovered while performing an experiment and these results force physicists to develop new or expanded theories. An example of this was described in Chapter I with the discovery of strange particles. Theory and experiment must ultimately be consistent. If experimental results show that an established theory is incorrect, the data results of the experiment are more than likely the suspect. If the same experiment is performed many times by numerous individuals, each time yielding the same results, a reconsideration of the physical theory may be in order. Theory and experiment keep each other honest by constantly checking and correlating their results.

It may be obvious by this time what role Fermilab experiments play in all this. Just because a theory is postulated, even by a reputable physicist, does not make it automatically correct. Many of the theories described in Chapter I (especially heavy quark flavors), are being tested in the Experimental Areas. Also, Fermilab experiments sometimes observe properties or make more precise measurements which challenge the predictions of theorists and force them to reevaluate their calculations. The two experimental descriptions which follow are only examples of similar testing that is being done elsewhere at Fermilab and at high energy accelerators all over the world.

B. Experiment E-705

Let's begin with the standard technical description of this experiment. Many of the terms and concepts will be unintelligible to anyone except a physicist on the experiment. Reading this type of description without any explanation of what it means is more frustrating than reading something in a foreign language, after all it's English and you ought to understand it right? Not so! Learning to "talk high energy physics" is like learning a foreign language. On to the description.

A Study Of Charmonium And Direct Photon Production

By 300 GeV/c Antiproton, Proton, Pi Plus, And Pi Minus Beams

"This Tevatron experiment will use the large aperture spectrometer of E-537 augmented by the addition of large angle electromagnetic shower counters to study charmonium production and direct photon production with a variety of particle beams (p, $\bar{p}$, π^+, π^-) at 300 GeV/c in the Proton West High Intensity Laboratory. The high resolution, high statistics measurements of the charmonium states will allow not only separation of the various gamma/psi states but also the detailed measurement of the angular distribution of the charmonium decays. The comparison of direct photon production by the various beams along with the observation of final state particles associated with the direct photons should allow the separation of $q\bar{q}$ and gq components of the production process."

The section below translates and defines the most important aspects of the above description. After reading through this section, go back and re-read the technical description again. You may not understand everything, but you will probably have a much better idea of what is going on in this experiment. Like any other foreign language, it takes repetition.

Transport To The Target

In order to get the most out of the next two sections (the Transport To The Target and Production Of Secondary Beams), the reader should have a basic knowledge of the geographical layout of the Experimental Areas and the naming convention used to identify devices in the controls computer's database. This information can be found in "The Experimental Areas Operations Training Manual For New Employees". It would also be helpful if the reader understands some of the basic principles of high energy physics beam optics. This information is described in "The Experimental Areas Beamline Transport System." It is not absolutely necessary to understand these terms, but even a little background will help tremendously.

The proton beam is extracted from the Tevatron and transported through the superconducting Right Bends to the Proton Area. The beam travels through several Proton Area enclosures till it reaches enclosure PW5 (see maps at the rear of this Chapter). At the downstream end of PW5, it is focussed by a quadrupole doublet composed of PW5Q1 and PW5Q2 (see Figure 1). The first lens of the doublet focusses the beam in the horizontal plane, the second one focusses in the vertical plane.

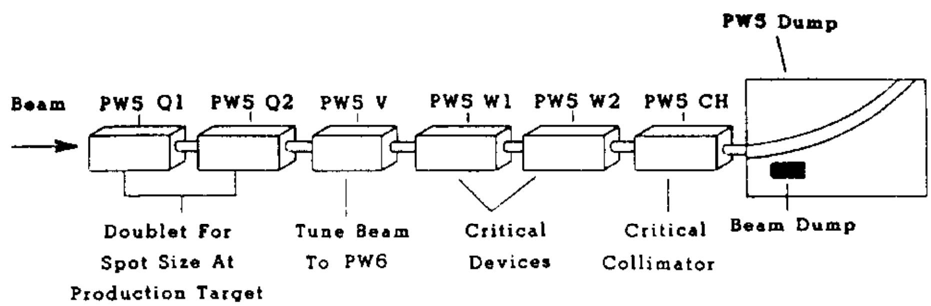


FIGURE 1

PW5V is used to tune the beam position into PW6. Just downstream, PW5W1 and PW5W2 bend the beam into one of two modes; the east-bend or west-bend mode. These two magnet strings and PW5CH are critical devices. The change from the east to west-bend mode is made remotely from the Operations Center, but it is important to understand the function of these elements.

In the <u>west-bend mode</u> , the beam is bent through the PW5 dump at an angle of 10.375 mRadians. The polarity of PW5W1 and PW5W2 are set to bend the beam to the west, and the current is set at a level which will provide the proper bend angle. Figure 2 shows a plan view of elements.

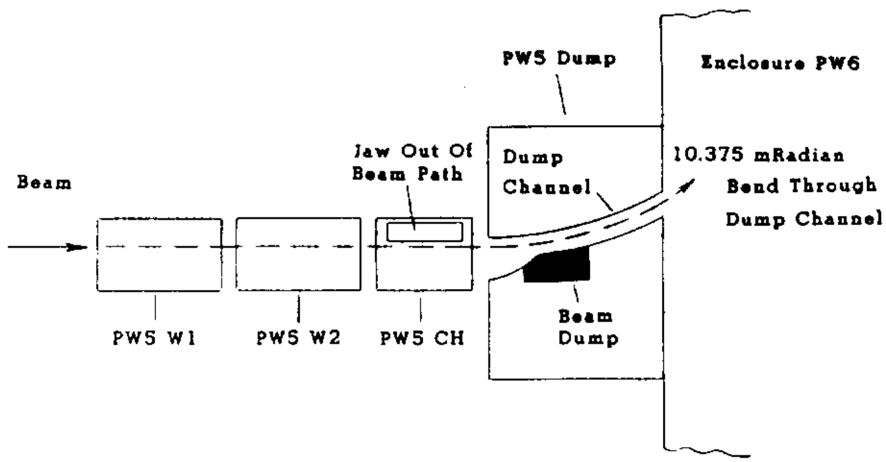


FIGURE 2

PW5CH is a specially designed collimator containing only one jaw. In the west bend-mode, the jaw is out of the beam path allowing the beam to enter the dump aperture. The beam must be in the west-bend mode in order to transport beam to enclosures downstream of PW5.

When the beam is in the <u>east-bend</u> mode personnel are allowed access to PW8 without disabling the P-West beam. When an operator switches the beam from the west to the east-bend mode, the following things happen remotely:

1. The current to PW5W1 is significantly reduced.
2. PW5W2 is turned off.

3. The jaw of PW5CH moves into the beamline.

When PW5W2 is turned off, the bending power of the two bend strings is significantly decreased and, in combination with the lower current level of PW5W1, the magnet string provides just enough bending power to bend the beam into the PW5 dump (see Figure 3). The insertion of the collimator jaw prevents beam from passing through the aperture into PW6. The geometry of the beam is shown in Figure 4.

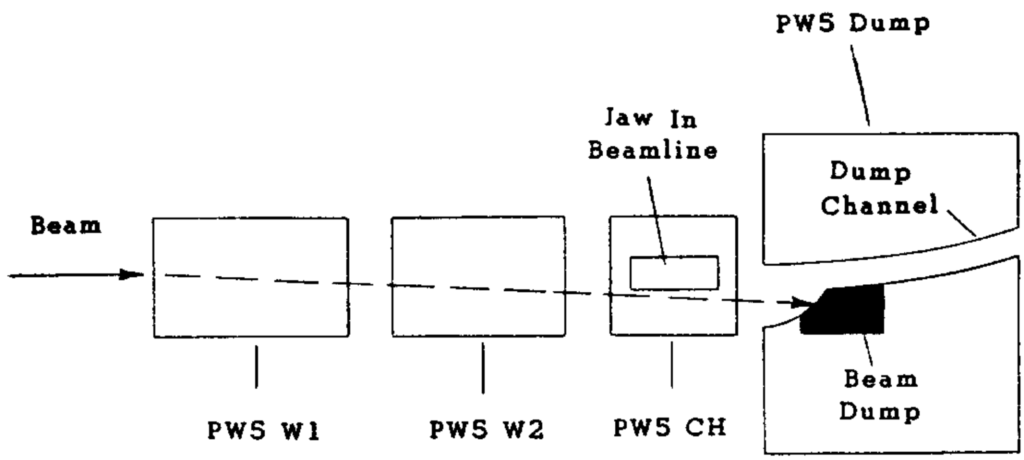


FIGURE 3

PW 5 Dump Trajectory

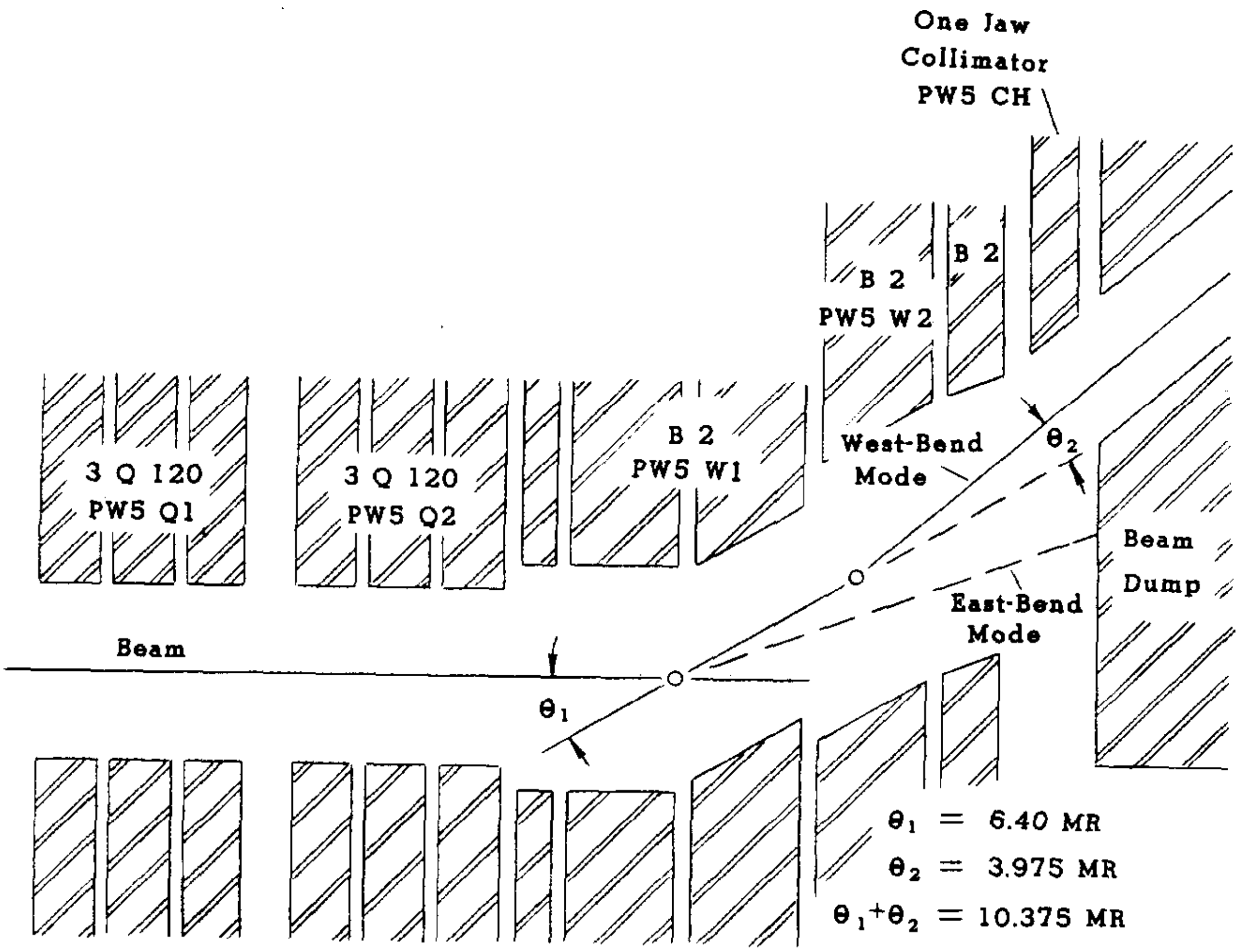


FIGURE 4

Production Of Secondary Beams

The protons leave enclosure PW5 and are transported to E-705's primary production target located in enclosure PW6. In order to successfully perform this experiment, E-705 must convert these protons into four types of secondary beams: protons (p), anti-protons ($\overline{p}$), positive pions (π^+), and negative pions (π^-). The secondary beams are produced by two different targeting modes:

1. The charged beam mode produces a proton, pi plus, and pi minus beam.
2. The neutral beam mode produces an anti-proton, pi minus, and electron beam.

In the charged beam mode, the incident protons enter PW6W1 and are bent to the center (bend point) of the target box magnet (PW6W2). PW6W2 then bends the beam to the target. Figure 5 shows the charged beam geometry.

E705 Targeting Geometry

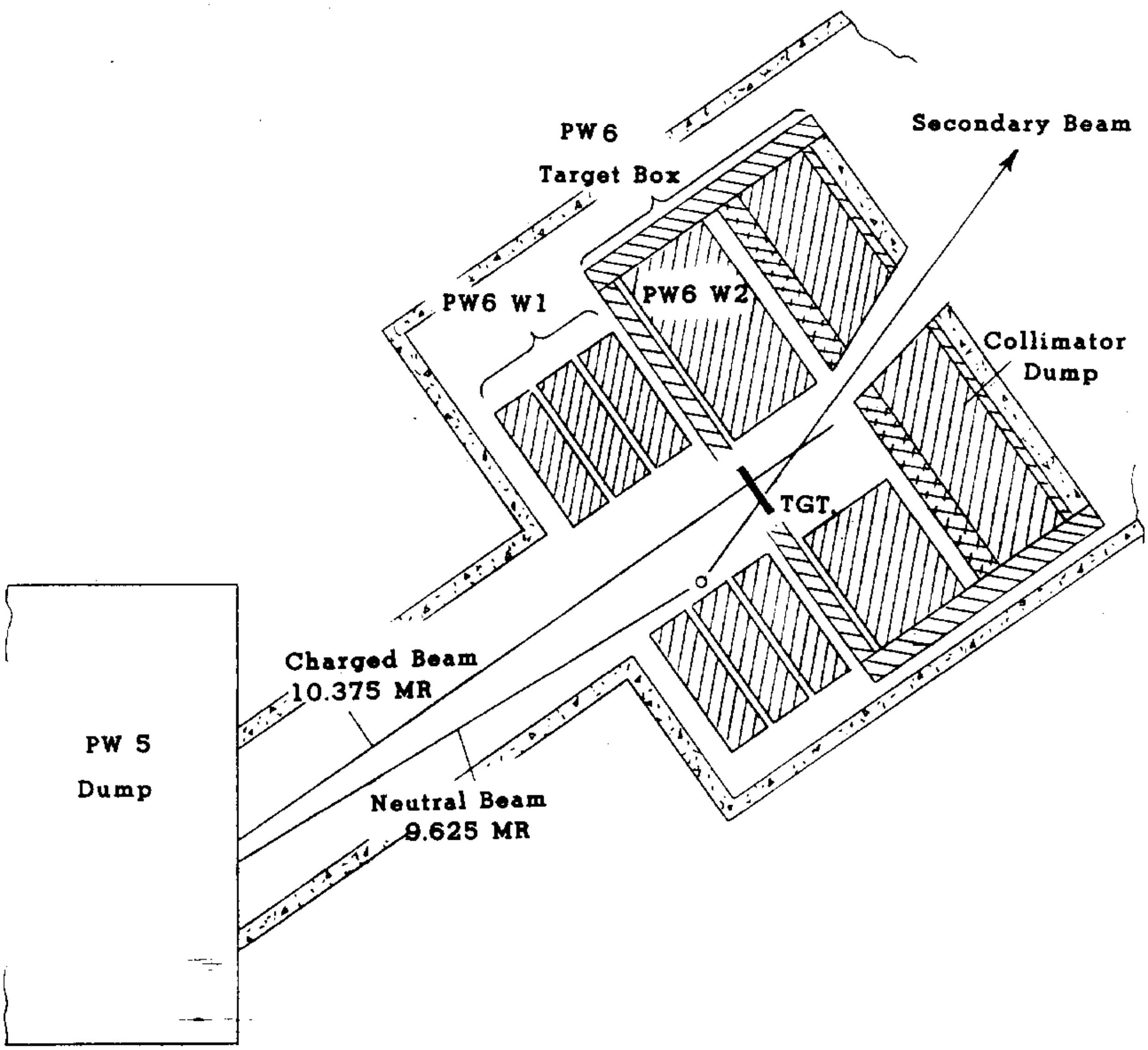


FIGURE 5

When selecting positively charged particles, the current and polarity of PW6W2 are set to bend 300 GeV/c positives through the target box channel. As the incident protons interact in the target, many types of particles with varying charge signs and momenta are produced. Because PW6W2's polarity is set to bend positives through the channel, the negatively charged particles are bent in the opposite direction into the collimator dump (see Figure 5). The neutrals which are produced go straight into the dump uneffected by the magnetic field of PW6W2. Positives with momenta below or above 300 GeV/c are also dumped into the steel housing.

In the neutral beam mode, the pre-target bend point is shifted to the east by bending the beam through the PW5 dump at an angle of 9.625 mRadians (see Figure 5). The change in entrance angle places the beam at a different position at the bend point of PW6W1. This means that the bend angle to the target must be increased, so PW6W1 must be set to a higher current. The beam is bent toward the target at zero degrees with respect to the target channel and secondary beam axis i.e., straight through the channel. Anti-protons are produced from anti-lambda zero decays ($\bar{\Lambda}^0 \rightarrow \bar{p} + X$). Although the decay products are charged particles, the parent particle is the uncharged anti-lambda, hence the name "neutral" beam mode. Only neutral particles should exit the target box channel, so the current setting on PW6W2 is very high sweeping many of the charged particles into the dump. The neutrals are uneffected by the magnetic field. Because the production angle is zero degrees with respect to the channel, the neutrals pass straight through the dump channel to downstream enclosures.

The secondary particles exiting the target box have a momentum spread of ± 15% 300 GeV/c. The focusing elements at the downstream end of the target box form a quadrupole triplet. The triplet focusses the central momentum particles to a tiny spot at the momentum slit located downstream (see Figure 6).

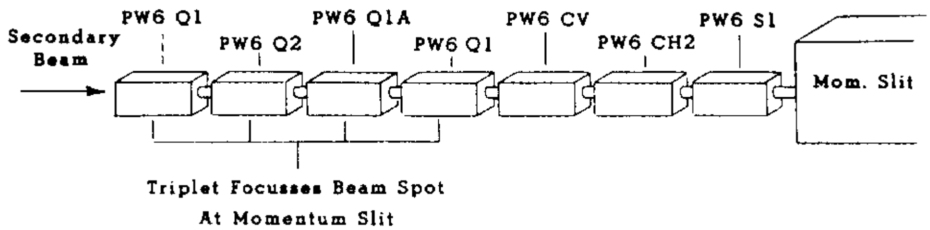


FIGURE 6

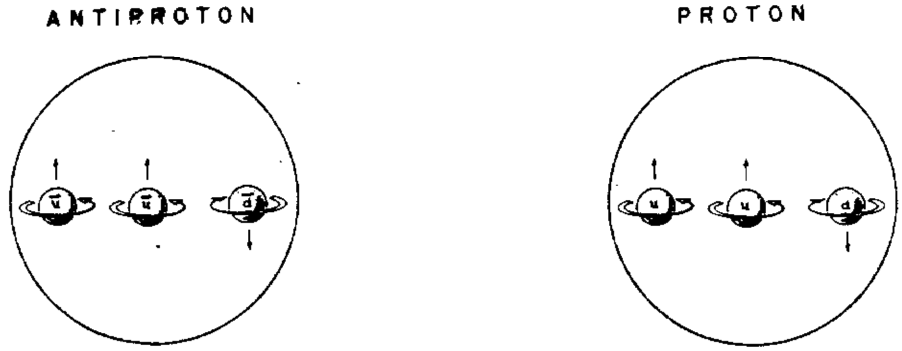
The momentum slit is a large precision collimator used to eliminate off momentum particles and select a precise momentum bite. The high precision of the momentum slit reduces the momentum spread to ± 5% 300 GeV/c. Thus a secondary beam with a defined momentum bite can be delivered to E-705's experimental target.

Physics Background

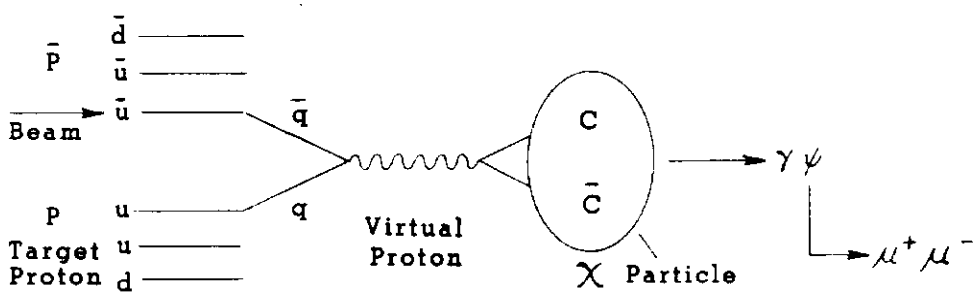
In Chapter I, we discussed a method for producing charmed particles called photoproduction. E-705 produces the charmed chi meson, but not by the photoproduction method. They use two additional production processes called quark antiquark annihilation ($q\bar{q}$), and quark gluon fusion (qg). Each process happens differently and demands a different kind of secondary beam to cause the interaction. E-705's technical description stated that they used 4 types of secondary beams: protons, antiprotons, pi plus, and pi minus. We will use two of these (protons and antiprotons) to illustrate the two production processes. Let's start with quark antiquark annihilation ($q\bar{q}$).

Whenever a particle and its antiparticle collide they annihilate each other i.e., totally destroy each other. For example, when an electron and a positron collide the individual particles fully destroy or annihilate each other. But the total energy of the particles cannot just disappear from the universe. Conservation laws demand that the total energy of the interaction be conserved, accounted for. Although the electron and positron no longer exist as separate particles after the collision, their combined energy is converted into a high energy photon.

The same principle holds true in quark antiquark annihilation. In order to produce chi particles by $q\bar{q}$ annihilation, we need a source of quarks interacting with a source of antiquarks. Because all matter is composed of protons which contain quarks, anything can be used as a target. E-705 used a liquid hydrogen target because of the simplicity of the hydrogen atom (one proton and one electron). The next thing we need is a source of high energy antiquarks to hit the target. This automatically eliminates the use of certain kinds of secondary beams. If you wanted the beam to contain antiquarks, you wouldn't use a proton or neutron beam because they consist of only u and d quarks. You could use a meson beam because all mesons contain a quark and an antiquark (see Chapter I on mesons). And in fact E-705 used two types of mesons as secondary beams (pi plus and pi minus). Pion beams produce the $q\bar{q}$ interaction, but each pion contains only one antiquark. One way to increase the probability of the interaction occuring is to use particles composed of more than one antiquark like the antiproton (see Figure below).

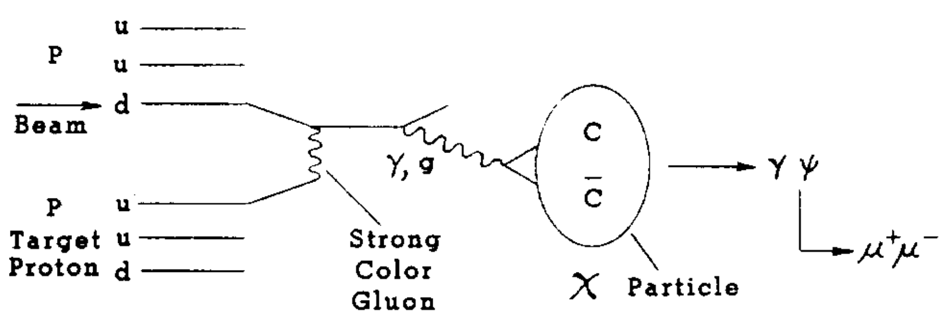


In the last section we described how E-705 used the neutral beam mode to produce anti-lambdas which subsequently decay to antiprotons. By using an antiproton beam (the source of antiquarks), and the hydrogen target (the source of quarks), we have everything we need to cause $q\bar{q}$ annihilation. If we hit the target with enough antiquarks (10^6 antiprotons) some of them should annihilate each other. The $q\bar{q}$ annihilation process is shown in the Figure below.



The protons in the hydrogen target contain 2 u quarks and a d quark. These are depicted in the Figure as 3 straight lines. The antiproton is identical except that it is composed of antiquarks also depicted as three lines. As an antiproton enters the target, one of the antiquarks in the antiproton annihilates one of the quarks in the target proton. The total energy of the interaction must be conserved so a virtual photon is produced as a result of the annihilation. The virtual photon exists for a very brief time and subsequently becomes a chi particle containing a charmed quark and a charmed antiquark.

The second process, quark gluon fusion (qg), happens differently. In Chapter I we discussed how gluons mediate the strong force which holds the nucleus together. The protons and neutrons in the nucleus are composed of u and d quarks which bind themselves together by the exchange of strong color gluons. In order to produce chi particles by qg fusion, we need two sources of quarks. We already have a target made of quarks, but we need an incident beam which is also composed of quarks. This eliminates the antiproton, pi plus, and pi minus beams because they all contain antiquarks which might possibly annihilate each other. But we can use a proton beam (see Figure below).



As the high energy proton beam enters the target, a color gluon is exchanged between one of the quarks in each particle and produces a high energy photon which subsequently becomes a chi particle. Sometimes the photon does not produce a chi particle in the interaction. When no chi is produced, the process is called direct photon production because the photon is produced directly from the qg fusion process. Having described the production of chi mesons, let´s examine some of the properties of the chi more closely.

The chi particle contains a charmed quark and a charmed anti-quark with the spins pointing in same direction. Each quark is like a spinning top. The direction of the spin is indicated in Figure 7 by the direction of the arrow. The concept of spin can be described by the right hand rule. If the thumb of the right hand points up, the spin direction points away from the body. If the thumb of the right hand points down, the spin direction points away from the body (see Figure 7).

χ Particle

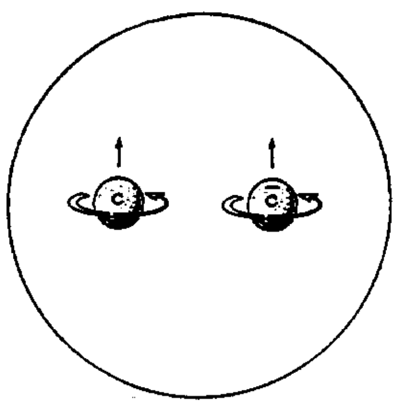
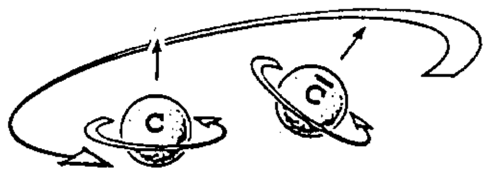


FIGURE 7

In Chapter I (Charmed Particles) we discussed how the chi decays to the lower mass psi. But there is more than one variety of chi particle. The chi comes in three types (states) each having a slightly different mass. The 0^{++} state has a mass of 3.41 GeV/c. The 1^{++} has a mass of 3.51 GeV/c, and the 2^{++} has a mass of 3.55 GeV/c. All three states contain the same quarks with the spins aligned in the same direction. The difference between the chi states is that the orbital angular momentum of the quarks is summed differently (see Figure 8). Orbital angular momentum is a measure of the way the spinning quarks orbit around each other within the particle. This is similar to the rotation of the earth on its axis, while simultaneously rotating around the sun. The sum of the orbital angular momentum and spin of charmed quarks is called a <u>charmonium</u> state.

Charmonium/Orbital Angular Momentum



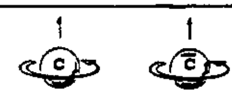
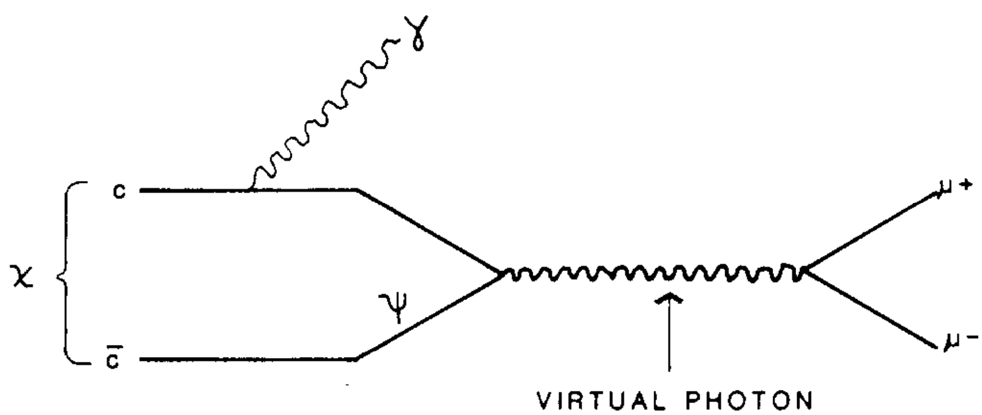
Momentum GeV/c	3.41	3.51	3.55
States	0^{++}	1^{++}	2^{++}
Quarks			
Angular Momentum	0	1	2

FIGURE 8

The greater the orbital angular momentum, the faster the two quarks rotate around each other. The magnitude of the rotation is assigned a number value. The 0^{++} has an angular momentum of 0, the 1^{++} has an angular momentum of 1, and the 2^{++} has an angular momentum of 2. Because the total mass of the particle includes orbital angular momentum, each of the three chi states has a slightly different mass. From an experimental perspective, the small difference in mass makes differentiating them very difficult. One way of doing this is by totaling the momenta of all final state particles which proceeded from the chi decay. The decay looks like this:

$$\chi \rightarrow \gamma\psi$$
$$\hookrightarrow \mu^+\mu^-$$

When a chi is produced (by either $q\bar{q}$ or qg), it decays into a psi in about 10^{-20} seconds and emits a photon. The photon, mediator of the electromagnetic force, indicates that the decay is an electromagnetic decay. The psi lives about 10^{-20} seconds then decays into a pair of oppositely charged muons. This process is called dimuon (2 muon) pair production. The Figure below shows the process.



The quark structure and spin directions of the chi and psi are identical. The difference is that the psi has no orbital angular momentum. The chi and psi decays occur so quickly that they don't even make it out of the experimental target. The only particles that make it through the target are the photon and the muon pair. These are the particles that E-705's apparatus is designed to trigger on. Conservation laws demand that the energy of the final state photon and muon pair equal the energy of the parent chi particle. The slightly different masses of the 3 chi states should therefore be reflected by slightly different masses in the decay products. By totalling the masses of the decay products, E-705 can determine which of the chi states produced a particular event. If the resolution of the detector is good enough to measure the decay masses precisely, the entire decay can be reconstructed.

There are three major reasons why E-705 is studying this particular decay. The first is to find out whether the production process of chi particles is dominated by quark annihilation, or by quark-gluon fusion. By using four different secondary beams as incident on their experimental target, they hope to answer this question. Secondly, they want to take data for each of the chi states and determine whether the 0^{++}, 1^{++}, and 2^{++} states are produced in different ways. By precisely measuring the energy of the photon that is emitted as the chi decays, E-705 will be able to measure the tiny mass differences of the three states. Other experiments have attempted this measurement, but the resolution of their apparatus was not high enough to conclusively observe these phenomena. E-705's apparatus has good enough resolution to observe the three chi states separately. Finally, many of the previously recorded psi events were produced in $e^+ e^-$ production. E-705 will determine whether hadronic production by $q\bar{q}$ annihilation and qg fusion is different than leptonic production. Theorists predict that the process is different, but they do not understand what the differences are.

The Apparatus

This section describes the operation of E-705's detector. The detector is designed to isolate the dimuon pair and the photon which result from the chi decay. If 10^6 anti-protons hit the experimental target per second, the detector will trigger about 1000 times. 100 of these triggers are dimuon pairs. About 80% come from psi decays with one half to one quarter of this 80% (20-40) coming from chi decays. Because the chi and psi decay before leaving the target, their existence must be infered from a reconstruction of the muon pair and photon. Figure 11 shows an elevation view of the apparatus.

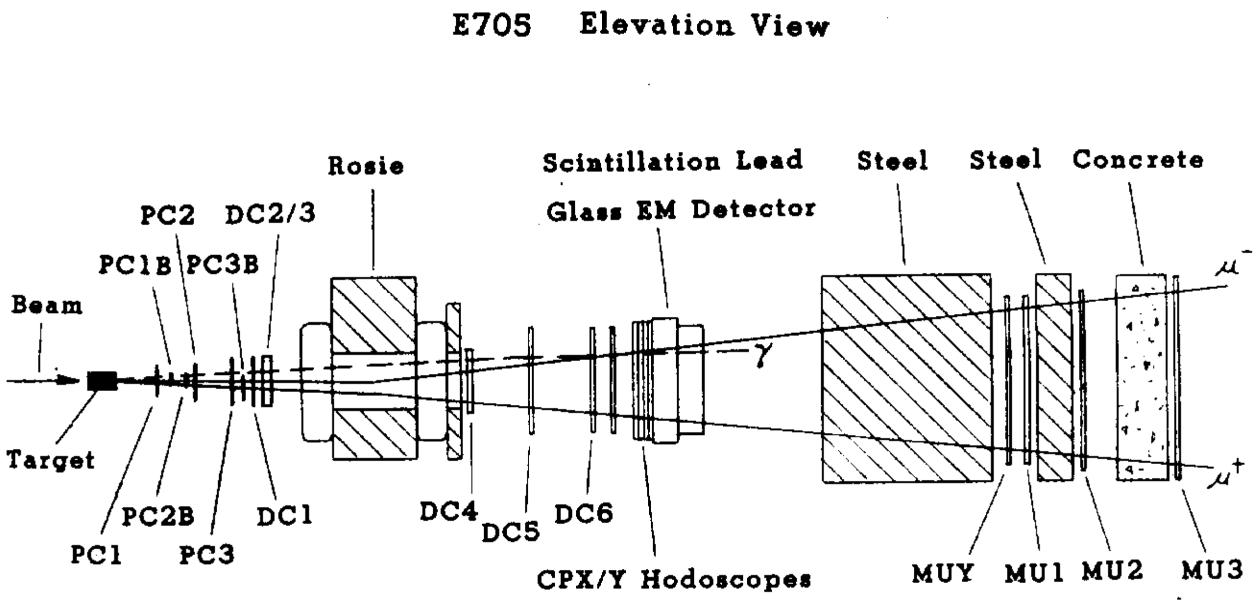

E705 Elevation View
Rosie
Scintillation Lead
Glass EM Detector
Steel
Steel
Concrete
PC2
DC2/3
PC1B
PC3B
Beam
γ
μ^-
μ^+
Target
PC2B
DC1
DC4
DC5
DC6
PC1
PC3
CPX/Y Hodoscopes
MUY
MU1
MU2
MU3

FIGURE 11

The first step is to measure the trajectory of the charged particles produced in the experimental target. After the psi particle decays into the dimuon pair, the muons and other charged particles produced in the target pass through a series of proportional chambers with 1-2mm wire spacing. PC1,2 and 3 are large chambers with a five inch central area which does not record hits from charged particles. Many of the background particles produced in the target pass through the center of the chamber without interacting. Only particle hits outside this area are recorded by the computer. PC1-3B are small chambers which have a sensitive area of only 5 inches. Particles which pass through the 5" hole in PC1-3, are recorded in PC1-3B. By comparing the position and time a hit occurs, E-705 can record the trajectory of many of the charged particles produced in the experimental target. Muon pair hits are distinguished from other particles by their opposite trajectories and common point of origin in the target (see Figure 11).

The next step is to measure the momentum of the muon pair. This is done by bending the muon pair through a large analysis magnet (Rosie) which has drift chambers at the upstream and downstream ends (see Figure 11). As the muon pair passes through DC1-3 its position is recorded by E-705's on-line computer. After being bent by the magnetic field of the analysis magnet, their position is noted by DC4-6 and also recorded by the computer. The momentum of the pair is calculated by the degree to which the pair is bent as it traverses the magnetic field. Although the momenta of background particles is also measured, the position and time of a muon pair hit happens simultaneously thus distinguishing them from the other particles.

The final muon identification and mass measurement is done by a series of hodoscopes that have steel and concrete shielding between them (see Figure 11). The first hodoscope is called CPX/Y. CPX/Y is composed of a series of vertical and horizontal scintillators that measure the position and momentum of the muon pair. At this point, there is still a large amount of charged particle background which must be eliminated. The muon pairs and charged particle background continue downstream to a large block of steel. The muon pairs pass through the steel easily, but most of the other particles are absorbed in the steel.

The second set of hodoscopes are located downstream with additional steel shielding for hadron absorbtion (Figure 11). MU1-3 are vertical scintillators, while the scintillators in MUY are mounted in the horizontal plane. As a muon pair passes through MUY and MU1-3, the position and time of the hits are noted by the fast logic of E-705's trigger processor. If the hits indicate a muon pair, the fast trigger tells the slow trigger logic to compute the mass of the muon pair based on the position and momentum measurements taken by MUY, CPX/Y, and DC4-6. If the effective mass of the pair is about the same as the mass of the psi particle, the event is recorded on tape. If the mass of the pair does not approximate the mass of a psi particle, the event is ignored.

The final part of the reconstruction is the measurement of the energy of the photon produced in the decay of the chi. Figure 11 shows the trajectory of the photon from the target. As the neutral photon passes through the first part of the experimental apparatus, it does not interact in the proportional or drift chambers and is uneffected by the magnetic field of the analysis magnet. Because the hodoscopes are looking for charged particles, the neutral photon passes through them without producing a signal. The energy of the photon and the time of the hit is measured by an electromagnetic lead glass detector (see Figure 11). This detector is composed of lead glass blocks and scintillating glass which have photomultiplier tubes attached to them. As the photon passes through the glass it produces light that is gathered by the photomultiplier tube and converted to a pulse height. A high energy photon gives off more light in the glass than a low energy photon. The height of the pulse is proportional to the energy of the photon. The electromagnetic lead glass detector does not trigger in conjunction with the muon hodoscopes. It operates independently of the on-line muon mass calculation done by the trigger processor. The photon energy measurement is combined with the muon pair data when the final reconstruction is written on tape.

By using a variety of beams and the high resolution detector, E-705 has accumulated a data sample of about 100,000 $\chi \rightarrow \gamma\psi$ decays. This large data sample will allow them to determine whether quark annihilation or quark gluon fusion dominates in the production of the chi particle. The excellent energy resolution of the apparatus for both charged particles and photons will allow them to make detailed studies on the three charmonium chi states individually. Finally, E-705 will answer some of the questions concerning the differences between chi production by electron positron interaction, and hadronic interaction of quarks.

C. Experiment E-691

Experiment E-691 is different than many of the experiments done at Fermilab. Most experiments are designed to search for a particular decay or measure a narrow set of parameters (experiment E-705 charmonium chi states). E-691's physics goals are broader than this. They are interested in studying any and all charmed particles produced by the photoproduction process. Because their physics goals are so broad, they have collected a much larger data sample than E-705. E-705 has accumulated several thousand charmonium chi events. E-691 has accumulated 80 million photoproduced hadronic events, 3% of which are charmed. Let's begin this section by looking at the technical description of the experiment taken from their proposal.

Charm Photoproduction With The

Tagged Photon Spectrometer

"The primary aim of this experiment is to study the properties of charmed particles and how they are produced by high energy photons. For E-691, we are adding to the Tagged Photon Spectrometer a vertex detector using silicon microstrip technology which has the capability of resolving the charm decay vertex.

The studies of charmed particles will focus on those particles such as F's which cannot be studied as easily as the D's at $e^+ e^-$ machines. The background suppression of the vertex detector will allow us to see F signals in a few decay modes, allowing a first look at F branching ratios. Since we will have a large clean sample of D mesons produced at high energy, we can look for excited charmed states. A large sample of D^o's identified without vertex information can be used for a precision measurement of the D^o lifetime. The comparison of photoproduction of heavy quarks with the photon-gluon fusion model has been carried out only in the most general way. E-691 should have clean D samples much larger than existing experiments, making possible detailed study of the charm production process."

This section begins with a description of the production of the secondary and tertiary beams. This is followed by a brief discussion of the physics background for the experiment and an explanation of the detector.

Production Of The Secondary Beam

E-691's beamline is designed to take machine energy protons from the Tevatron and convert them into a "tagged" photon beam. This process starts at the target box located in enclosure PE3. As the 800 GeV protons from the Tevatron interact in the primary production target, many particle types and signs are produced. The production angle of the beam is 0° with respect to the secondary beam axis, so the neutral particles produced in the target travel straight through the target box channel uneffected by the magnetic field of the target box magnet (PE3D). Charged particles are bent into the dump. Figure 1 is a schematic drawing of the target box area.

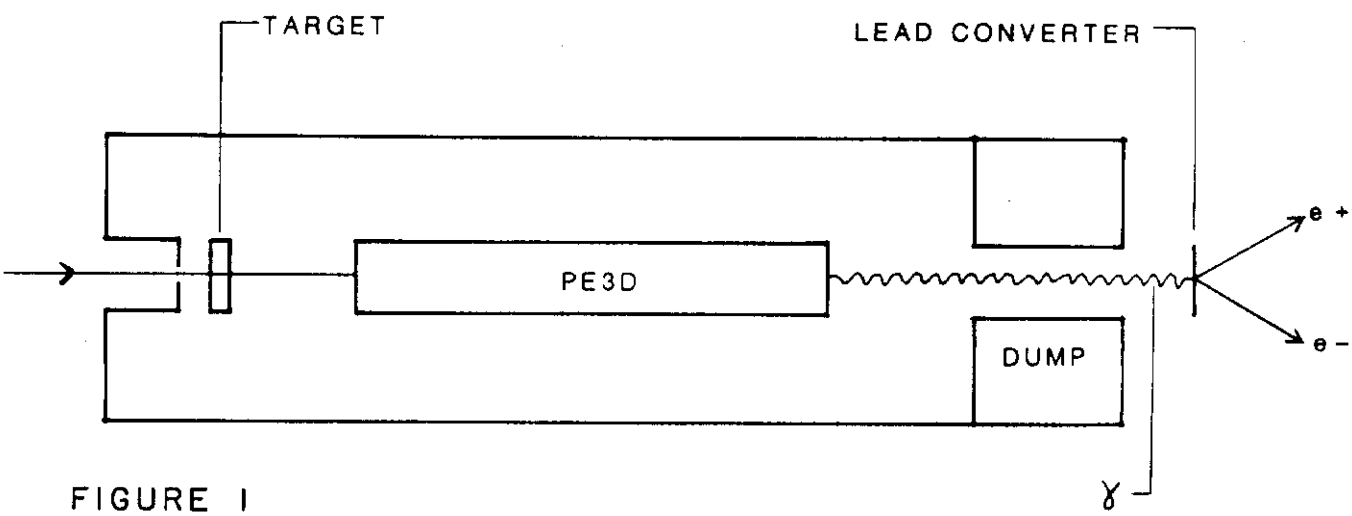


FIGURE I

E-691 is interested in all high energy photons produced in the target. Because all neutral particles pass through the channel, the goal is to separate the photons from the other neutral particles. Many of these are neutrons. The photons and neutrons hit a lead converter placed at the downstream end of the target box (see Figure 1). Most of the neutrons do not interact in the lead and proceed to a neutral dump located downstream. Many of the photons interact in the lead producing electron positron pairs. The positrons are bent away from the beamline and the electrons are transported to another lead converter located downstream in enclosure PE5. The beamline is tuned to transport electrons of a particular energy (250 GeV/c). Starting off with particles having a variety of energies (at the target), only 250 GeV/c electrons reach the downstream enclosures.

Production Of The Tertiary Beam

The electrons are transported to a lead target in enclosure PE5. As they interact in the lead, high energy photons are once again produced (see Figure 2).

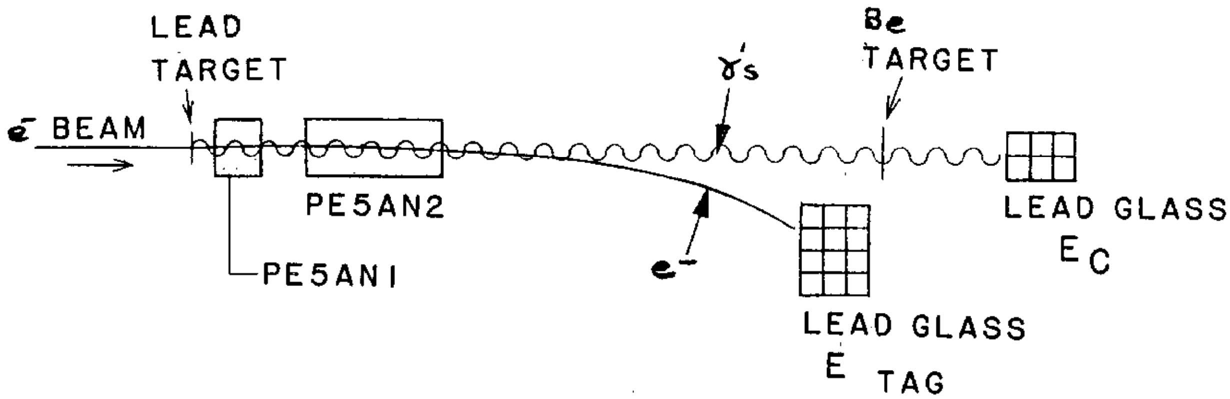


FIGURE 2

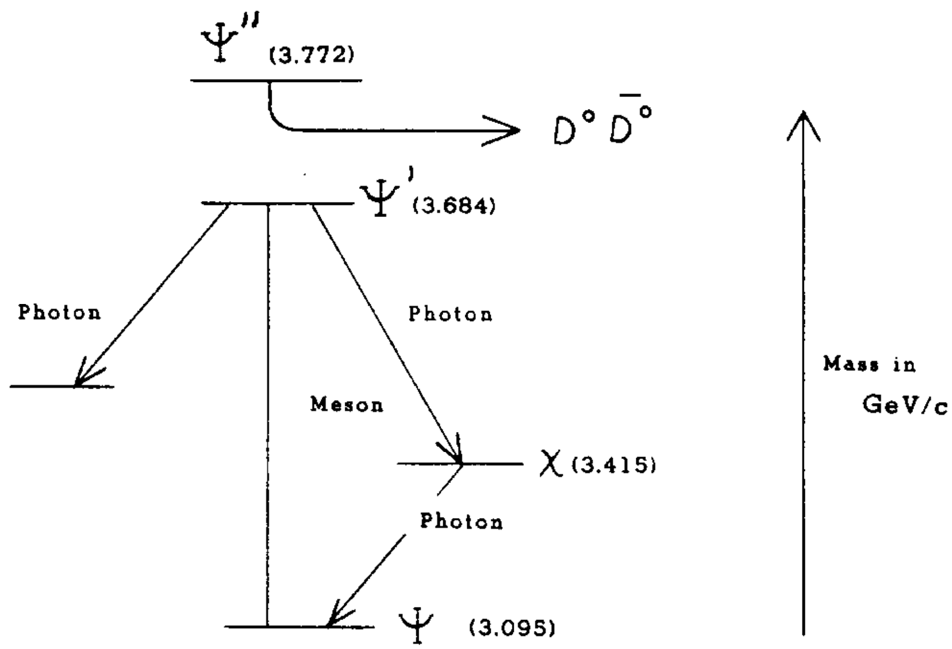
$$\boxed{E_\gamma = E_{BEAM} - E_{TAG} - E_C}$$

This part of the beam transport is called the "tagging system". The last section described how the high energy photons from the production target were converted into an electron beam by passing them through a lead converter. The electrons were then transported downstream to PE5 and reconverted into a photon beam by passing them through another lead converter. Why is this necessary? The photons produced in the production target have a wide variety (wide band) of momenta. E-691 must know the momentum of the photons which interact in their experimental target in order to reconstruct the final events. One way of producing a photon beam with a known (tagged) momentum is to convert the photons coming from the production target into an electron beam, select a particular electron momentum bite, then reconvert the electrons back into photons.

Here's how the tagging system works. As electrons pass through the second lead converter, they produce photons as they pass through the lead. The electrons which pass through the converter are bent into an array of lead glass blocks by PE5AN1 and 2 (see Figure 2). As the electrons interact in the glass, they generate a pulse height which is proportional to their energy. The pulses are generated by photomultiplier tubes and fed into E-691's computer. The photons produced in the converter continue downstream and pass through the experimental target. Some of the photons interact in the target, others do not interact and hit a lead glass array located downstream. As the photons penetrate the glass, they generate a pulse height which is proportional to their energy. The pulses are generated by photomultiplier tubes attached to the glass blocks and fed into E-691's computer. The formula for tagging (calculating) the energy of the photon beam is shown in Figure 2. The energy of the photons is equal to the energy of the incident electron beam (E_{beam}) minus the energy of the electrons in the lead glass (E_{tag}) minus the energy of the photon (E_c).

Physics Background

Charmed particles were discussed previously in Chapter I. The mass chart below shows a few of them and indicates their mass in units of GeV/c.



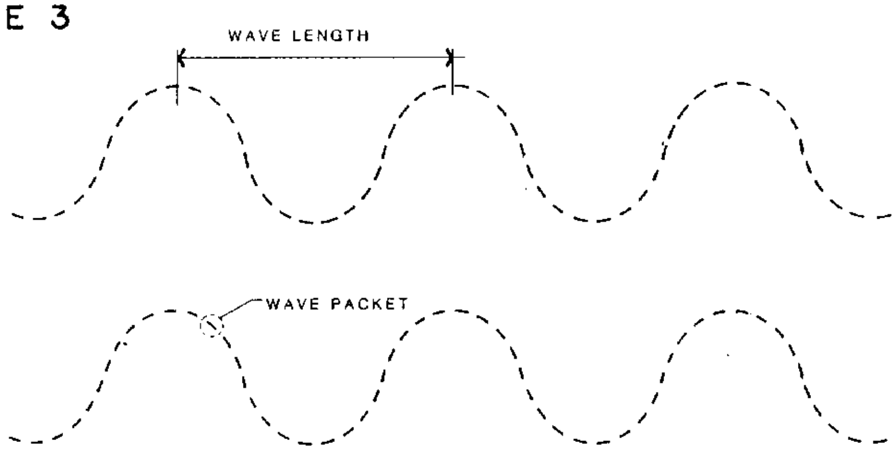
Charmed particles can be produced in a variety of ways. The three processes discussed so far are:

1. Leptonic production through e^-e^+ pair annihilation (the discovery of the Ψ/J particle).
2. Hadronic production through quark anti-quark annihilation (E-705).

3. Hadronic production through quark gluon fusion (E-705).

E-691 will use another type of production process called photoproduction through photon gluon fusion. The photoproduction of charmed particles occurs when a photon is in a virtual state containing charmed quarks. Virtual states were discussed previously in Chapter I. Figure 3 reviews the nature of virtual states.

FIGURE 3



A small fraction of the time photons are virtual while exhibiting all the properties of a photon. Theory predicts that a certain amount of the time the virtual state will contain a virtual charmed quark and antiquark. If another particle interacts with the virtual quarks knocking one away from the other, their effective (combined) mass becomes very large and they are forced to become real. In this experiment, a gluon from one of the target protons is the particle which provides the kick. The process is shown below in Figure 4.

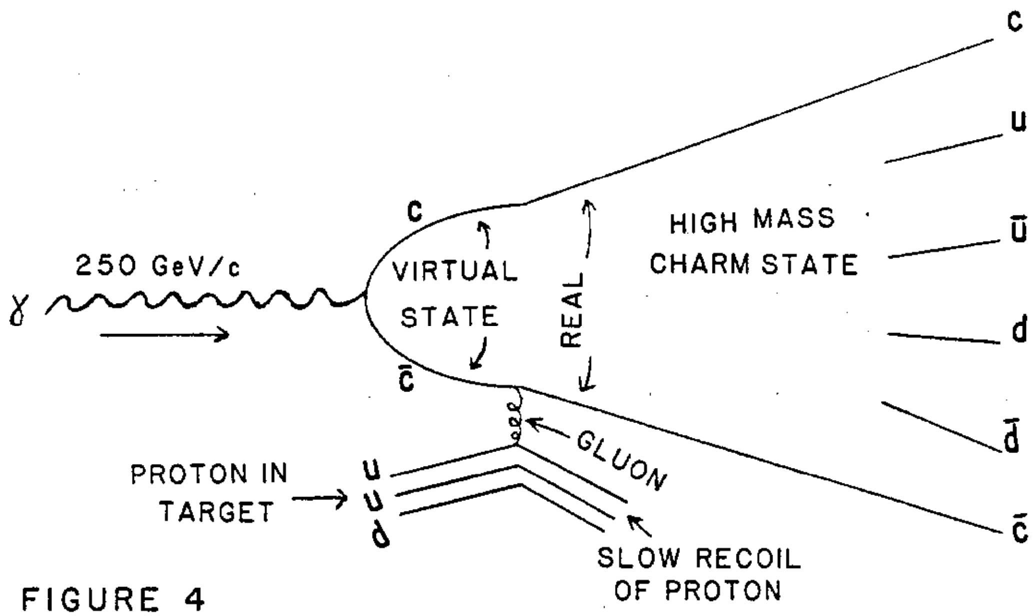


FIGURE 4

In Figure 4, the incident photon enters the experimental target from the left. If the virtual state contains a charmed quark and antiquark, a probability exists that charmed particles will be produced. As the the virtual $c\bar{c}$ pair passes near a proton in the target, a gluon from the proton interacts with it (see Figure 4). When the virtual quarks experience the force of the gluon, they are knocked apart. As they move away from each other and their effective mass increases, they are forced to become "real". The result is a high mass charm state containing various types of quarks. The total energy of the charmed state varies between 4-12 GeV/c. As long as the total energy of the charmed state is conserved, a wide variety of final state mesons and baryons may be produced in the interaction.

One possible interaction is the decay:

$$\gamma p \longrightarrow M_{c\bar{c}}\ p^{*}$$

$$p^{*} \rightarrow p, \quad p\pi^{o}, \quad p\pi^{+}\pi^{-}$$

$$M_{c\bar{c}} \rightarrow D^{o}\bar{D}^{o}X \quad \text{or} \quad F^{o}\bar{F}^{o}X \quad \text{or} \quad \Lambda_{c}\bar{\Lambda}_{c}X$$

X : n π's K's
n : 0 to 12

In this decay, the incident photon interacts with a gluon producing a high mass $c\bar{c}$ state ($Mc\bar{c}$). The P^{*} indicates particles that may be produced by the slow recoil of the target proton (see Figure 4). In the above example, the $Mc\bar{c}$ state produces charmed mesons (D^{O}, $\bar{D}^{O}$, F^{+}, F^{-}) or two charmed baryons (Λ_c, $\bar{\Lambda}_c$). The X symbolizes a variety of lower mass mesons such as pions and kaons. Many charged particles can be produced in an interaction, but typically 8 are produced.

There are 5 reasons why E-691 is performing this experiment:

1. There is still a question about the exact mass of some charmed particles (F meson). E-691 will study the masses of all charmed particles and provide additional data about the masses of this family of particles.

2. They want to study the <u>mechanism</u> of photoproduction of charmed particles. Other experiments have investigated leptonic and hadronic production. E-691 hopes to understand the photoproduction process and how it relates to the other production mechanisms.

3. They want to measure how charmed particles decay by reconstructing the final state particles.

4. They want to measure the lifetimes of charmed particles.

5. They want to compare their data with the current theories of photon gluon fusion.

<u>The Apparatus</u>

E-691 has accumulated data on all types of charmed interactions. Because of the all inclusive nature of the data sample, their apparatus and trigger processing electronics is very complicated. This section gives an overall view of the apparatus, and shows how it works by describing one possible decay reconstruction. The decay is:

$$
\begin{array}{l}
\gamma p \longrightarrow D^0 \bar{D}^0 \pi^+ \pi^- \pi^0 \\
\qquad\quad \bar{D}^0 \hookrightarrow K^+ \pi^- \qquad \pi^0 \hookrightarrow \gamma\gamma \\
\qquad\quad D^0 \hookrightarrow K^- \pi^+
\end{array}
$$

Figure 5 shows a plan view of the apparatus. The experimental target is 5cm of beryllium. The first part of the detector is called the vertex detector and has 9 planes of silicon microstrip detectors containing 6000 channels, enabling the experiment to measure the position of a particle to an accuracy of 15 microns. This part of the apparatus is very important because it measures the vertices of charmed particle decays produced in the initial interaction in the target (see Figure 6).

PLAN VIEW

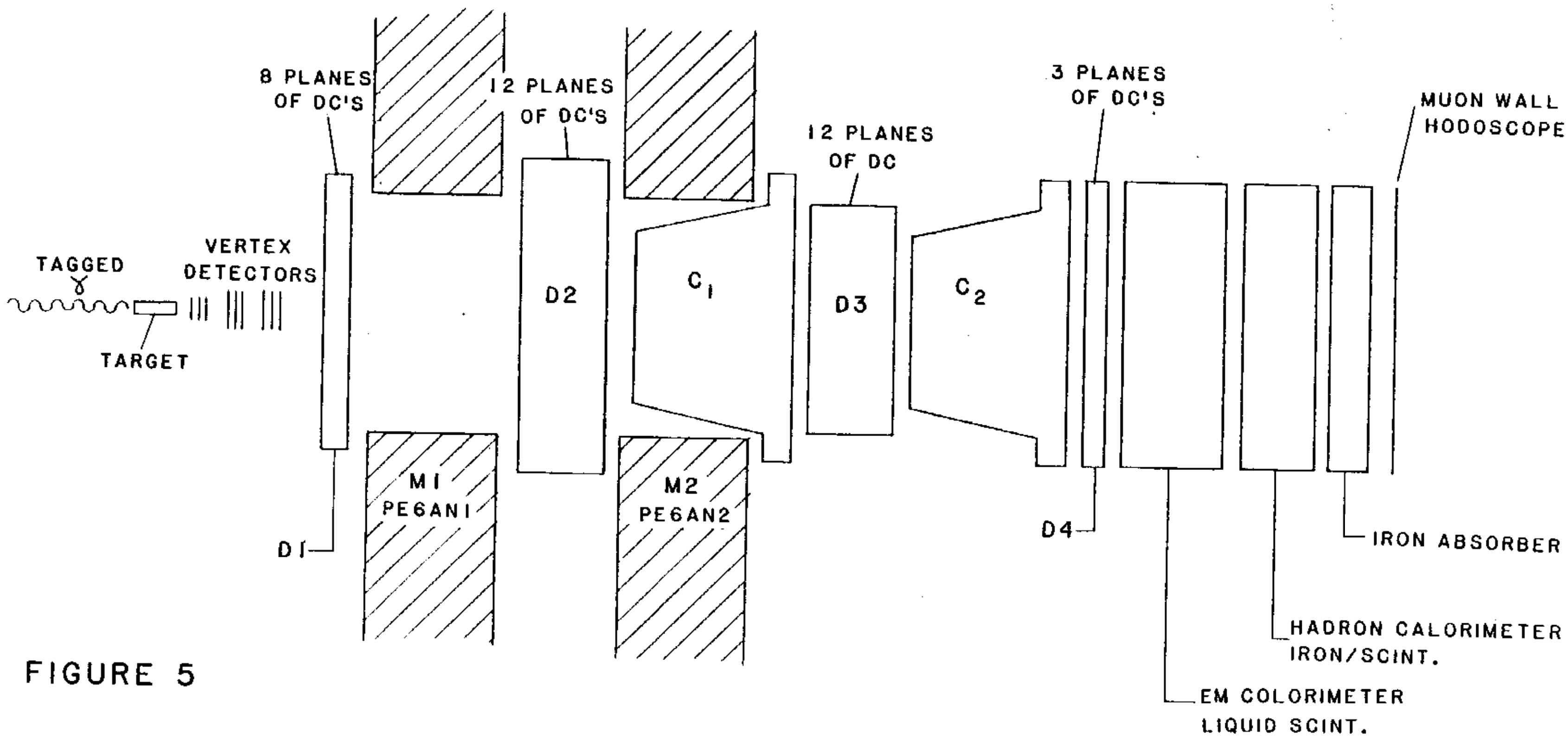


FIGURE 5

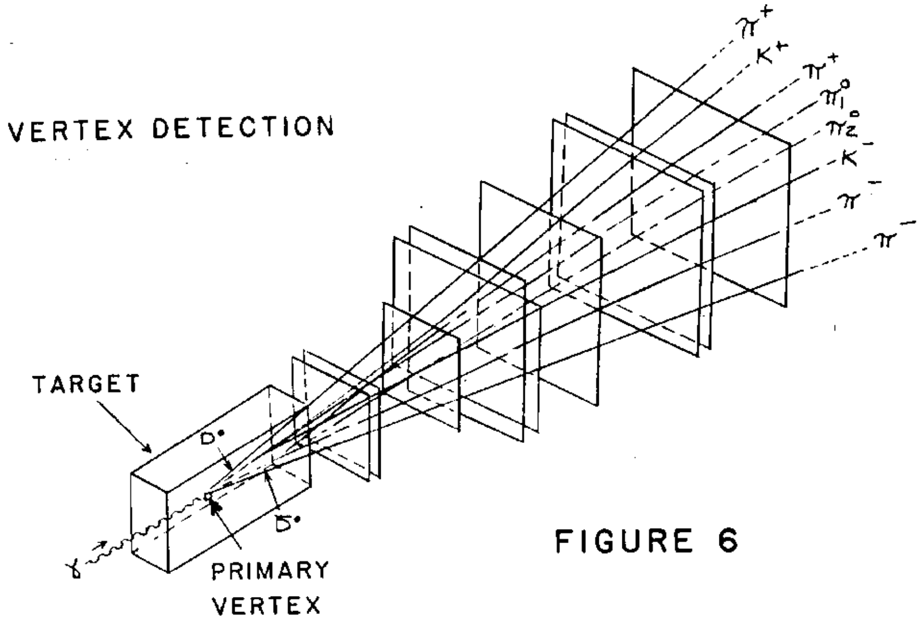


FIGURE 6

As the incident photon (γ) interacts in the target, a variety of charmed particles are produced. The high resolution of the vertex detectors allows the reconstruction of the charm decay vertices back to the point of the initial interaction (primary vertex).

The apparatus contains 4 sets of drift chambers (DC) (see Figure 5). These are used in conjunction with 2 analyzing magnets (PE6AN1 and 2) to tag the momentum of all charged particles. Charged hits are initially recorded on D1. After being bent by the magnetic field of the analysis magnets, their trajectories are measured by the position of hits on the downstream drift chambers. The trajectories form a geometry which is traced back through the vertex detector to the primary vertex in the target where the interaction took place (see Figure 7). By measuring the amount of the bend angle produced by the analysis magnets, E-691 can determine the momenta of the charged particles.

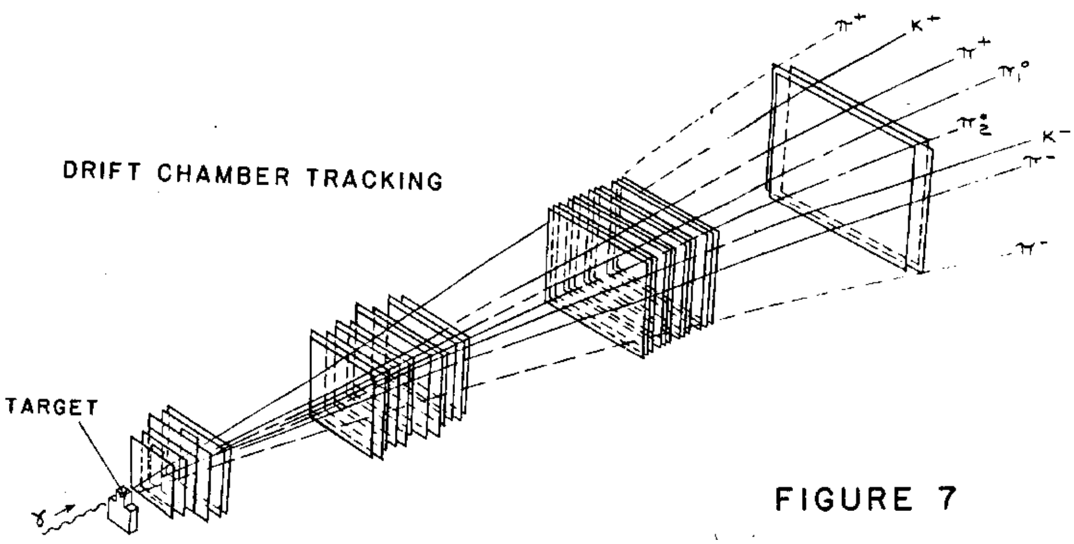


FIGURE 7

Although the drift chambers and analysis magnets can measure the momenta of charged particles, they can not identify the type of particles which penetrated the apparatus. The Cerenkov counters are used to identify particle type (see Figure 5). Cerenkov counters are usually filled with some type of gas. When a particle penetrates the Cerenkov counter moving faster than the speed of light in the gas, it emits Cerenkov radiation which gives a measurement of a particle's mass/type. In this experiment, the majority of the particles which are identified are pions and kaons. Just downstream, the electromagnetic calorimeter contains liquid scintillator and is used to detect photons. Using our hypothetical decay, we see that the neutral pion decays in about 10^{-16} seconds into two photons which are detected in the electromagnetic calorimeter.

$$\gamma p \rightarrow D^0 \bar{D}^0 \pi^+ \pi^- \pi^0$$
$$\hookrightarrow \gamma\gamma$$

The hadron calorimeter detects neutral hadrons such as neutrons (see Figure 5). It is composed of iron and scintillator. As the neutrons interact in the iron, they produce a shower of particles which are detected in the scintillators. The energy of the neutron is calculated by totaling the energies of the particles contained in the shower. Immediately downstream is an iron absorber which absorbs all particles except muons. Muons pass through the iron easily and are detected in the muon wall hodoscope located downstream (see Figure 5). The hodoscopes are used to identify them as muons.

The tracks of a typical charmed decay are represented schematically in Figure 8. E-691's apparatus is designed to detect and record these particles as they penetrate the various parts of the detector.

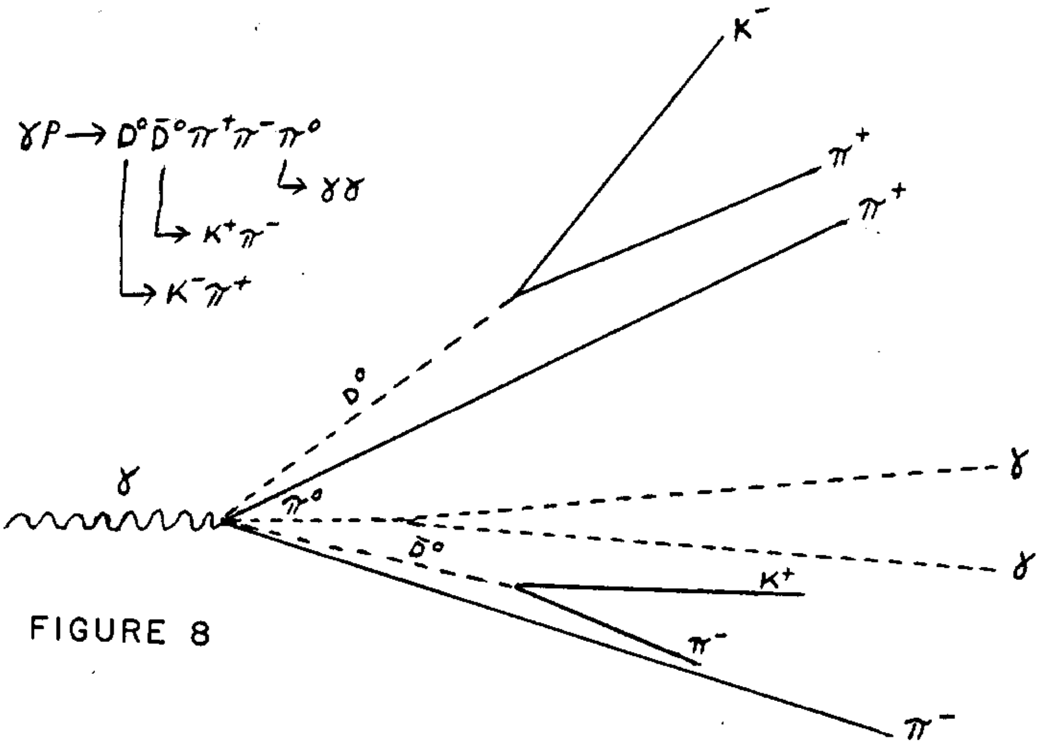


FIGURE 8

In this example, the incident photon interacts with a proton in the target producing the above particles. Initially, five particles are produced; two D mesons and three pions. The two D mesons subsequently decay into pions and kaons and the neutral pion decays into two photons. Figure 9 shows the quark recombination of the D^0 meson.

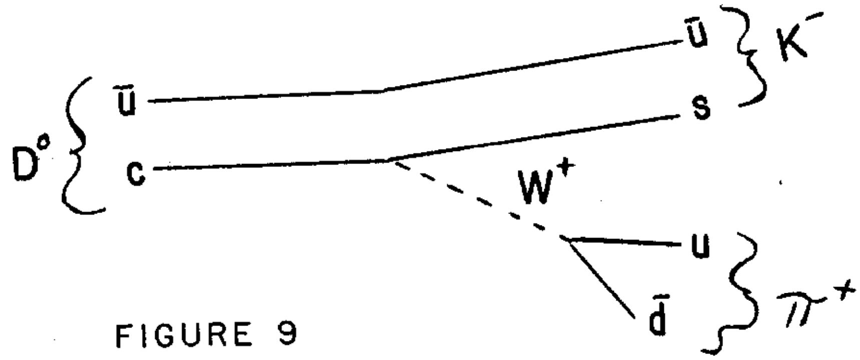


FIGURE 9

The D^0 is composed of a charmed quark and an anti-up quark. As the meson decays the anti-up quark remains unchanged and the charmed quark changes into a strange quark. The energy difference between the charmed and strange quarks is given off as a W boson, which decays into a positive pion.

Once the particles from the above decay penetrate the apparatus and are recorded on tape, E-691 can retrace the angles of the hits, determine particle momentum from the drift chambers, and identify particle types with the Cerenkov counting system. E-691's data sample will significantly increase the amount of recorded photoproduced charmed events.

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